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Analytical Fatigue Life Determination based on Residual Strength Degradation of Composites

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

2018 Technical Review

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National Institute for Aviation Research

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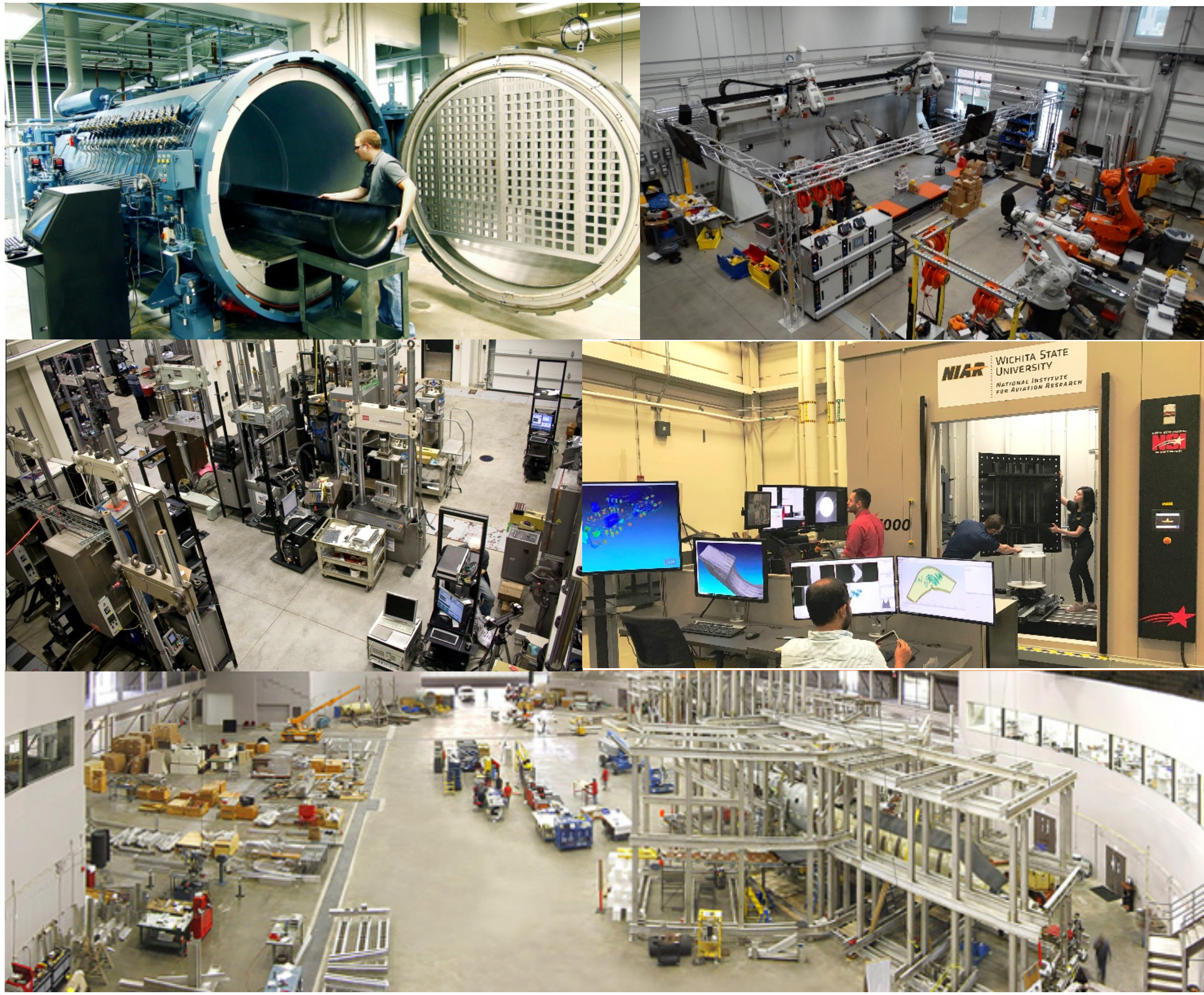


Variable Amplitude Fatigue Damage Growth (Background)

- Due to the anisotropy and heterogeneous nature of composites, fatigue damage growth characteristics of composites are complex and predictive methodologies are at their infant stages.
- Therefore, overly conservative assumptions are made for fatigue life assessment without taking full advantage of fatigue capabilities of composites.
- In order to design efficient composite structures, a greater understanding of fundamentals of fatigue damage initiation and growth characteristics of composite is needed.
- Need to understand the interaction of high-cycle (low stress) and low-cycle (high stress) fatigue on the life assessment of composite.

The primary goal of this research is to investigate the fatigue damage growth of composites under variable amplitude fatigue loading.
The secondary goal of the program is to develop tools for determining the residual strength degradation or wearout.

Building-Block Validation Road Map

Method Development		Coding	Structural Application

Method Development

- *Fatigue Test*
- *High-Fidelity Inspections*
- *High-Fidelity Analysis*

→ *Fatigue Life Prediction using Residual Strength Degradation (ST Method)*

Coding

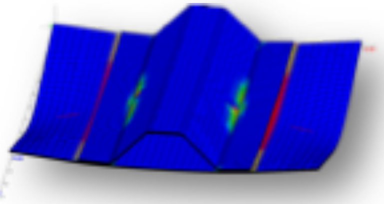
Verification & Validation

↓

Development of User Subroutine

↓

Incorporate into BSAM/Abaqus



Structural Application

Structural Analysis (TBD)

↓

Structural Test Validation

The primary goal of this research is to develop techniques to enhance advanced material characterization and structural certification aided by high-fidelity damage modeling and efficient protocol for structural substantiation.

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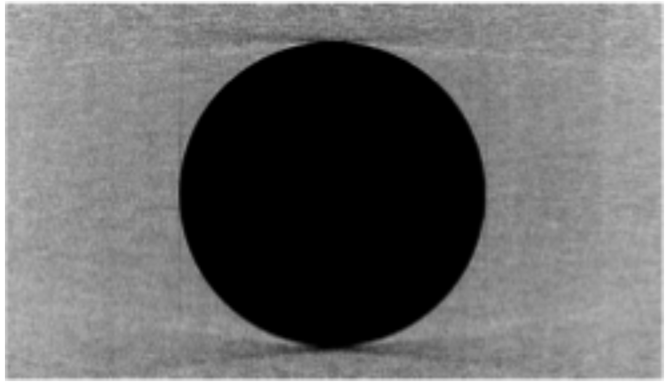
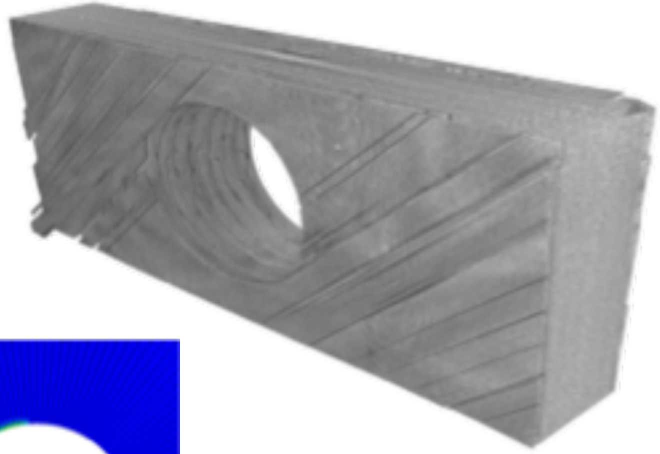
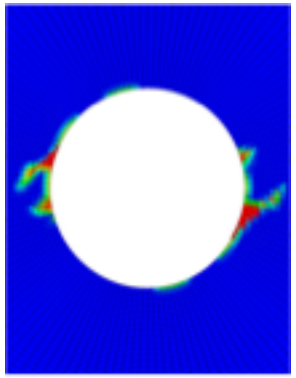
Overview of the Presentation

- Development of Strength Tracking (ST) Methodology
  - Variable Amplitude Fatigue Analysis
  - Validation
- High-Fidelity Inspections for Damage Characterization
  - X-Ray Computed Tomography (XCT)
  - High-fidelity inspection database
- High-Fidelity Finite Element Analysis
  - Regularized Extended Finite Element Analysis (Rx-FEM)
  - Validation with XCT and test results

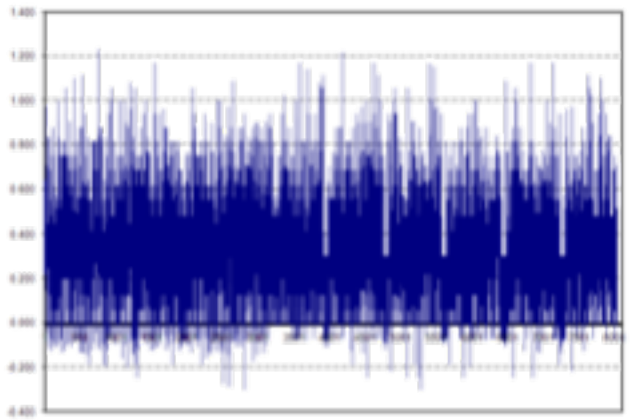






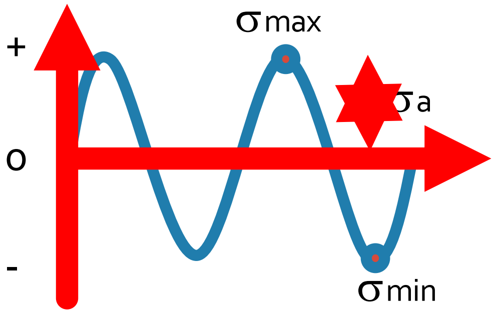
Development of Strength Tracking (ST) Methodology

Variable Amplitude Fatigue Testing & Analysis



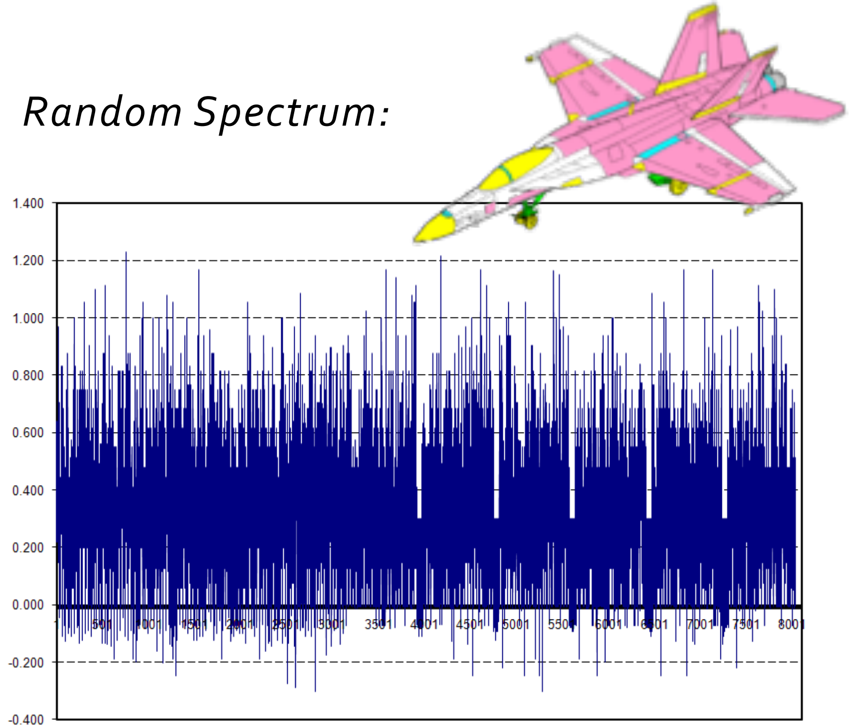
Constant Amplitude vs. Variable Amplitude (Spectrum)

Constant amplitude:



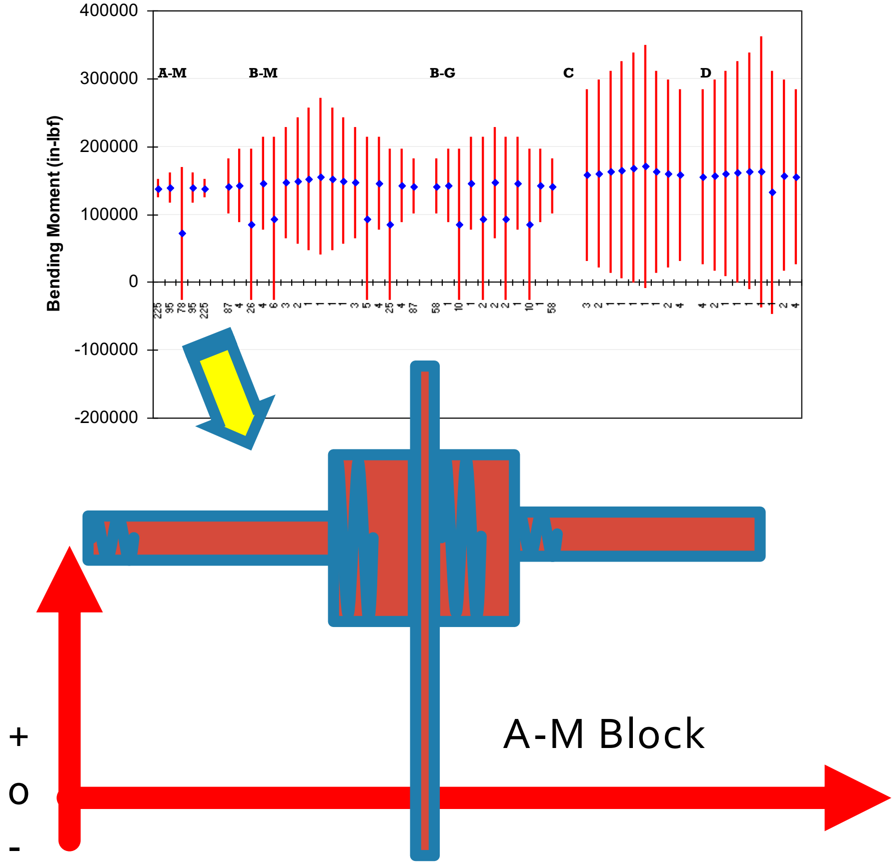
$A = (\sigma_{max} + \sigma_{max})/2$

Random Spectrum:



REF: Seneviratne, W., *et.al.*, "Durability and Residual Strength Assessment of F/A-18 A-D Wing-Root Stepped-Lap Joint," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and the Centennial of Naval Aviation Forum, September 2011.

Block Spectrum:

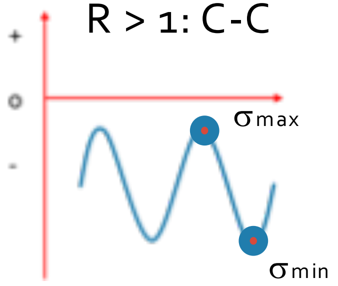


REF: Seneviratne, W. P., "Fatigue Life Determination of a Damage-Tolerant Composite Airframe," Wichita State University, December 2008.

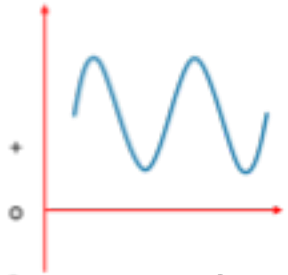
Stress Ratio (R)

R = min / max stress

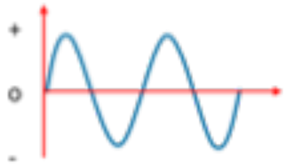
R > 1: C-C

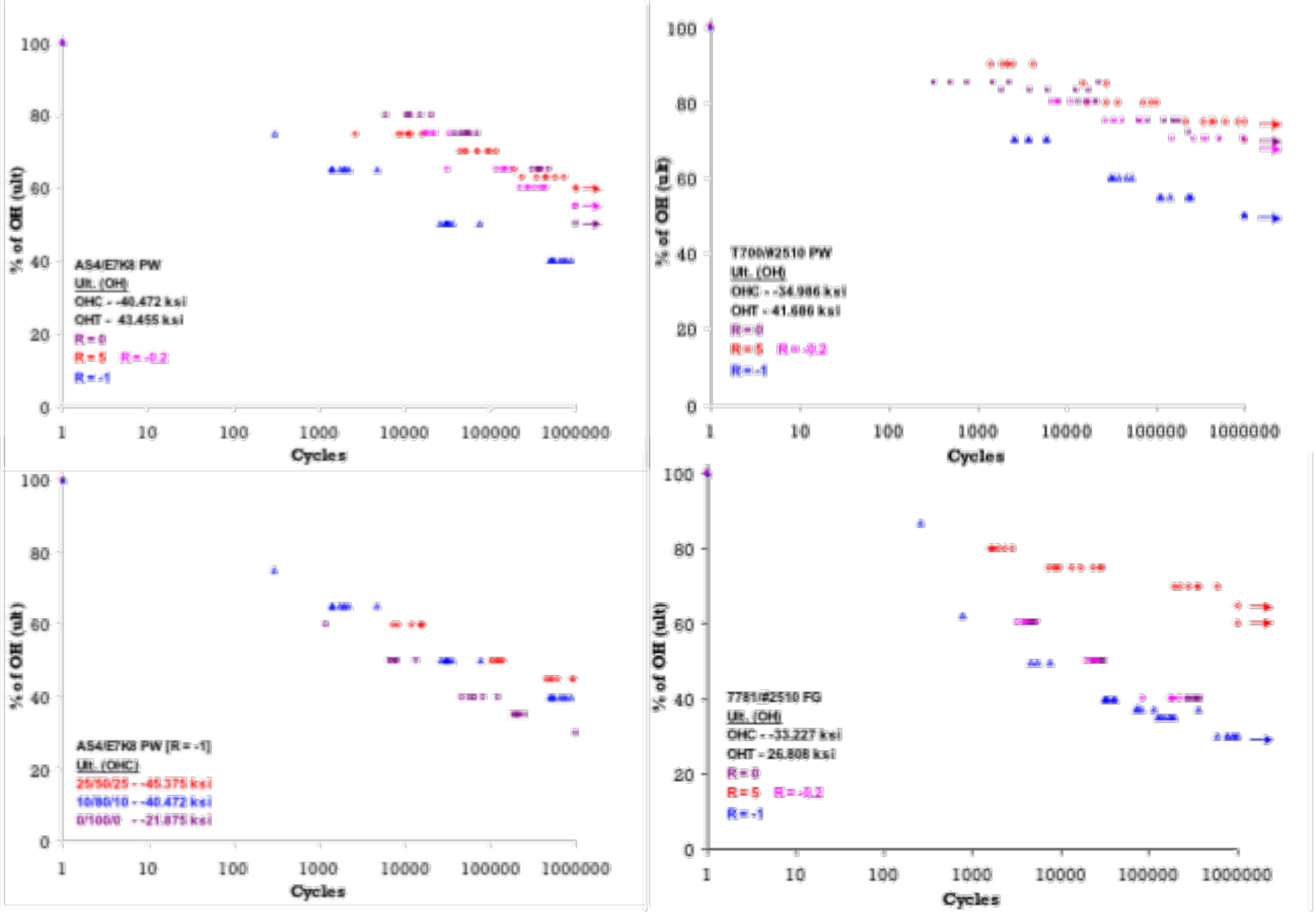


1 > R > 0: T-T



R < 0: C-T





Ref: DOT/FAA/AR-10/6

Fatigue Scatter Analysis Techniques

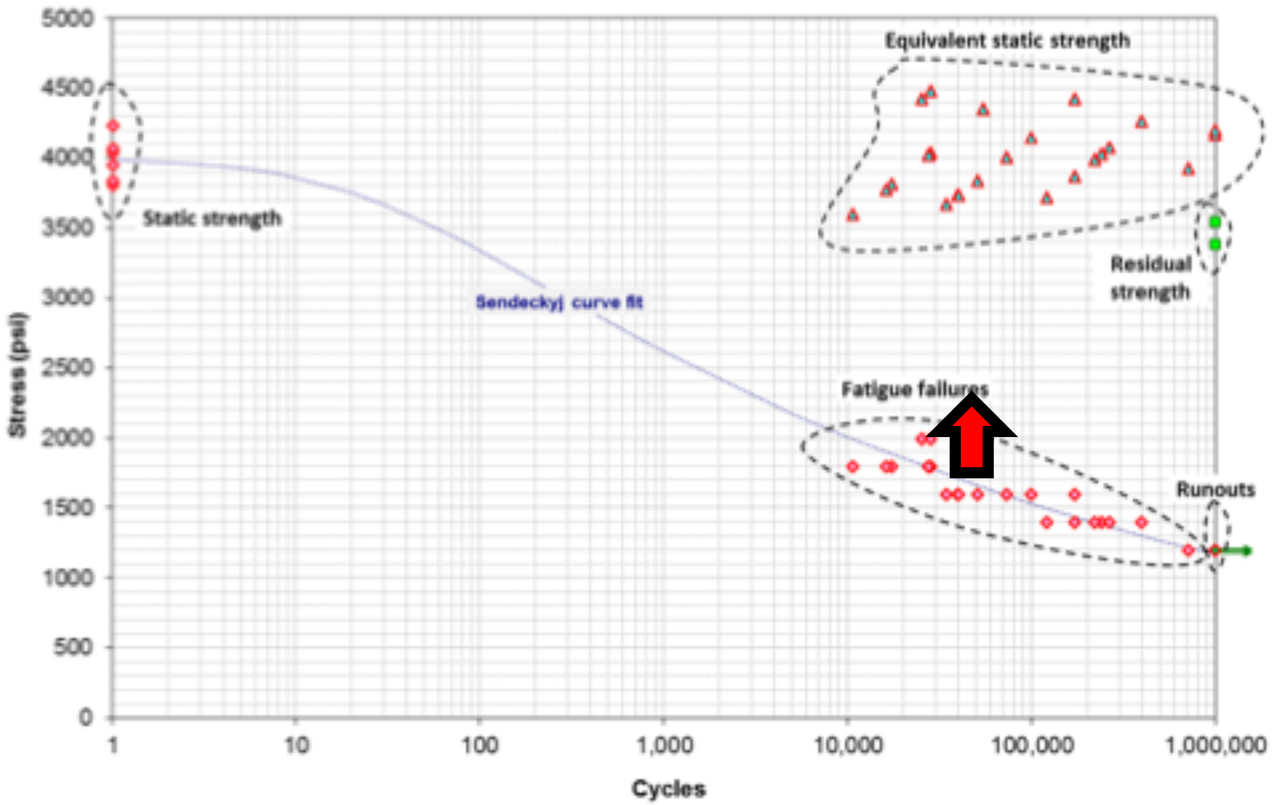
- Individual Weibull
- Joint Weibull

$$\sum_{i=1}^{M}\left\{n_{fi}\cdot\left[\frac{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}\cdot\ln(x_{ij})}{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}}-\frac{1}{\hat{\alpha}}-\frac{\sum_{j=1}^{n_{fi}}\ln(x_{ij})}{n_{fi}}\right]\right\}=0$$

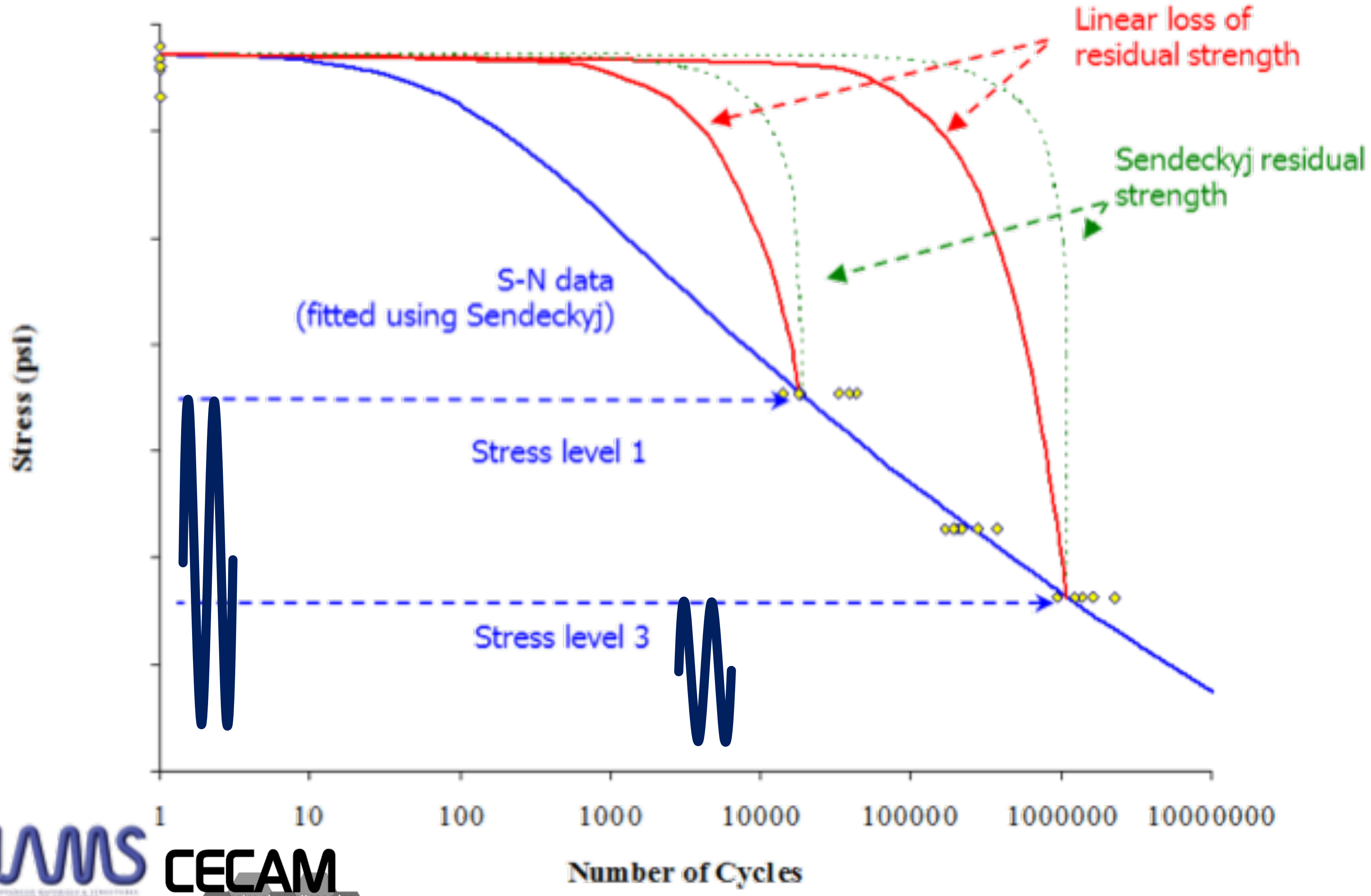
- Sendeckyj Equivalent Strength Model

$$\sigma_e=\sigma_a\left[\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S}+(N_f-1)\cdot C\right]^S$$

Data Pooling Techniques

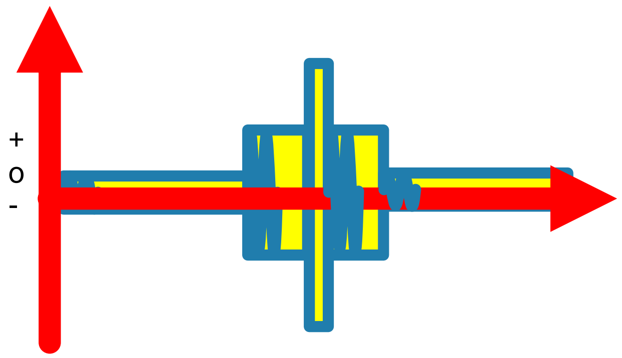


Wearout under Constant Amplitude Fatigue

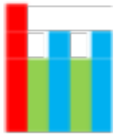


$$\sigma_r = \sigma_e + \left(\frac{\sigma_a - \sigma_e}{N_f(\sigma_a)} \right) \cdot n_f$$

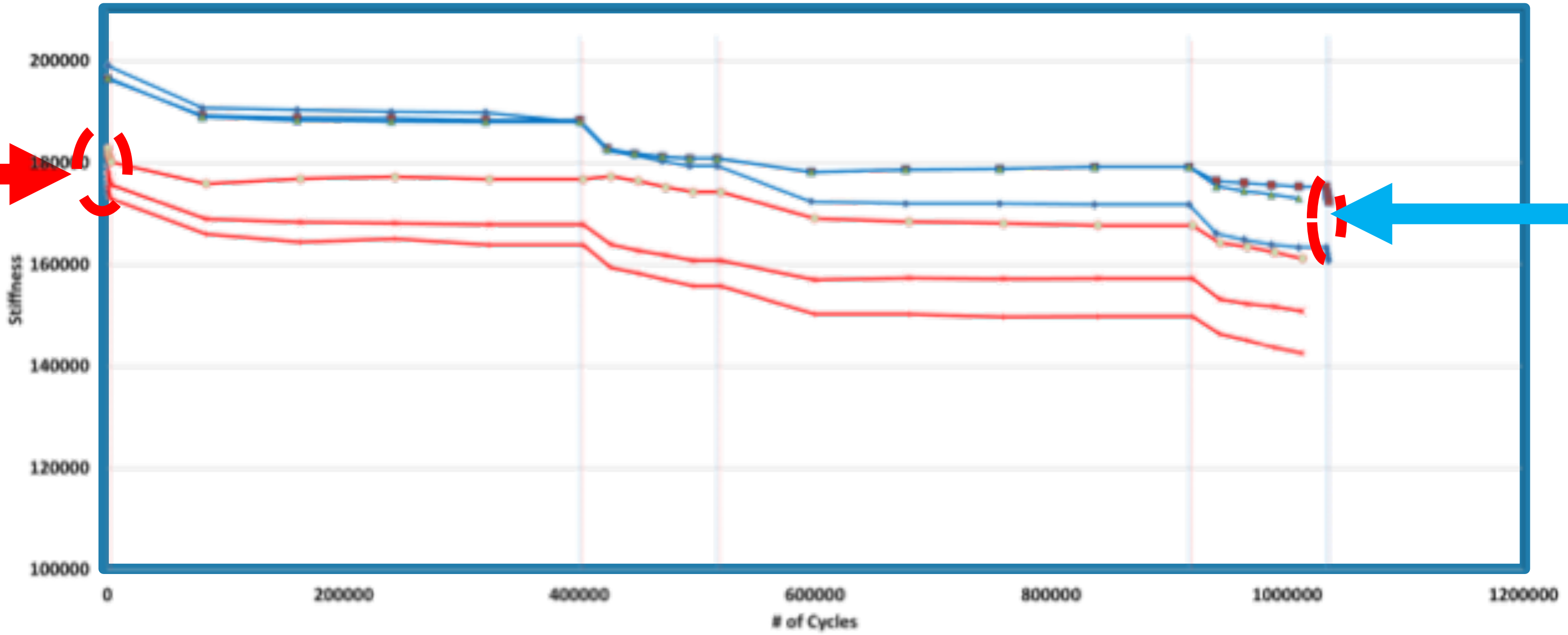
$$\sigma_r = \sigma_a \left[\left(\frac{\sigma_e}{\sigma_a} \right)^{1/S} - C(n_f - 1) \right]^S$$



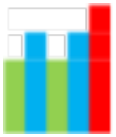
Residual Strength Degradation - Variable Amplitude Fatigue



Fatigue Profile 5	
Stress Level	**# of Cycle**
70	3000
40	400010
55	116330
40	400010
55	116330



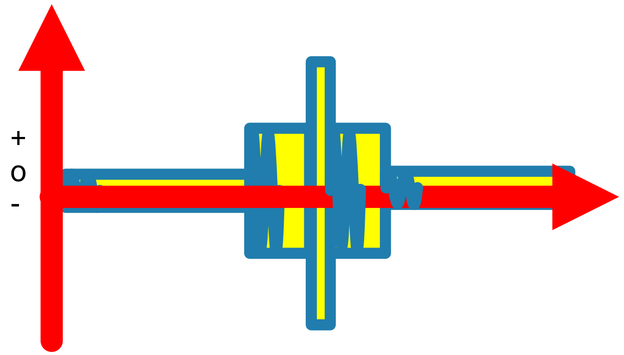
Fatigue Profile 6	
Stress Level	**# of Cycle**
40	400010
55	116330
40	400010
55	116330
70	3000



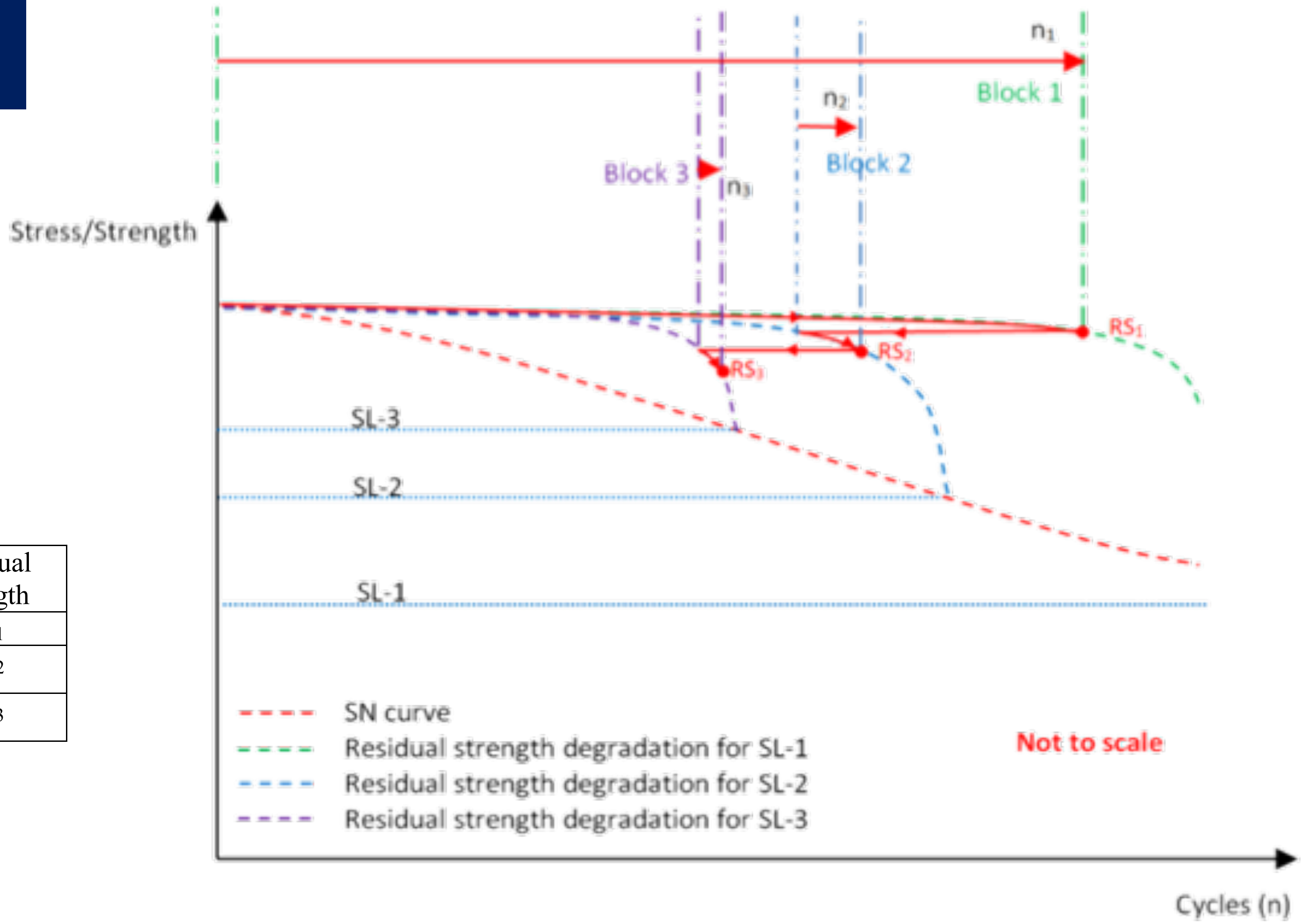
REF: Seneviratne, W., and Tomblin, J., **Load Sequencing Effects and Damage Growth Retardation of Composites**, FAA Joint Advanced Materials & Structures (JAMS), Grapevine, TX, 2016.

Strength Tracking (ST) Method

Fatigue Model Based on Residual Strength Degradation (Wearout)

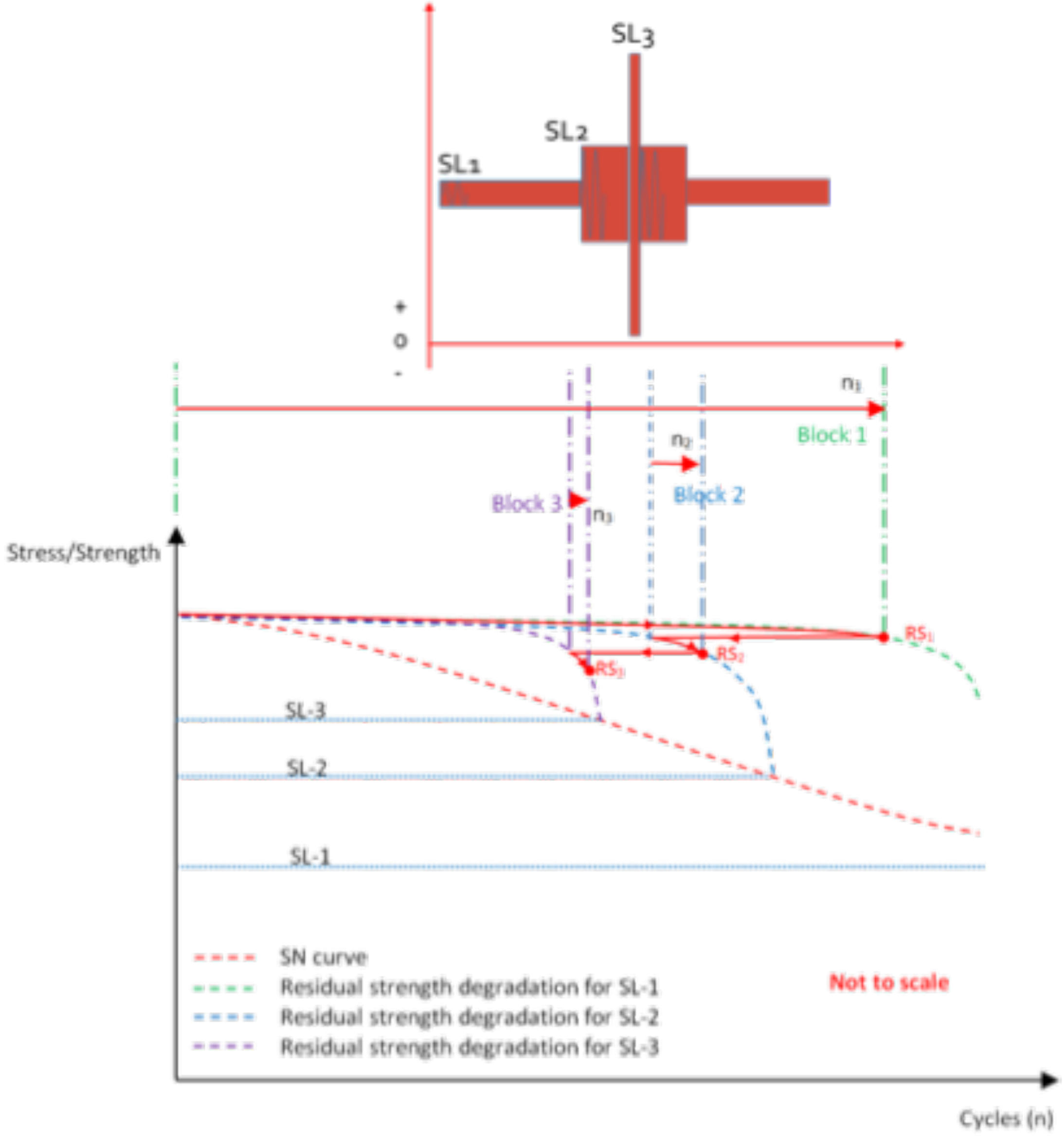


Block No.	Stress Ratio	Stress Level	Number of Cycles in Block	Cumulative Cycles	Residual Strength
1	R = -1	SL-1	n_1	n_1	RS_1
2	R = -1	SL-2	n_2	$n_1 + n_2$	RS_2
3	R = -1	SL-3	n_3	$n_1 + n_2 + n_3$	RS_3

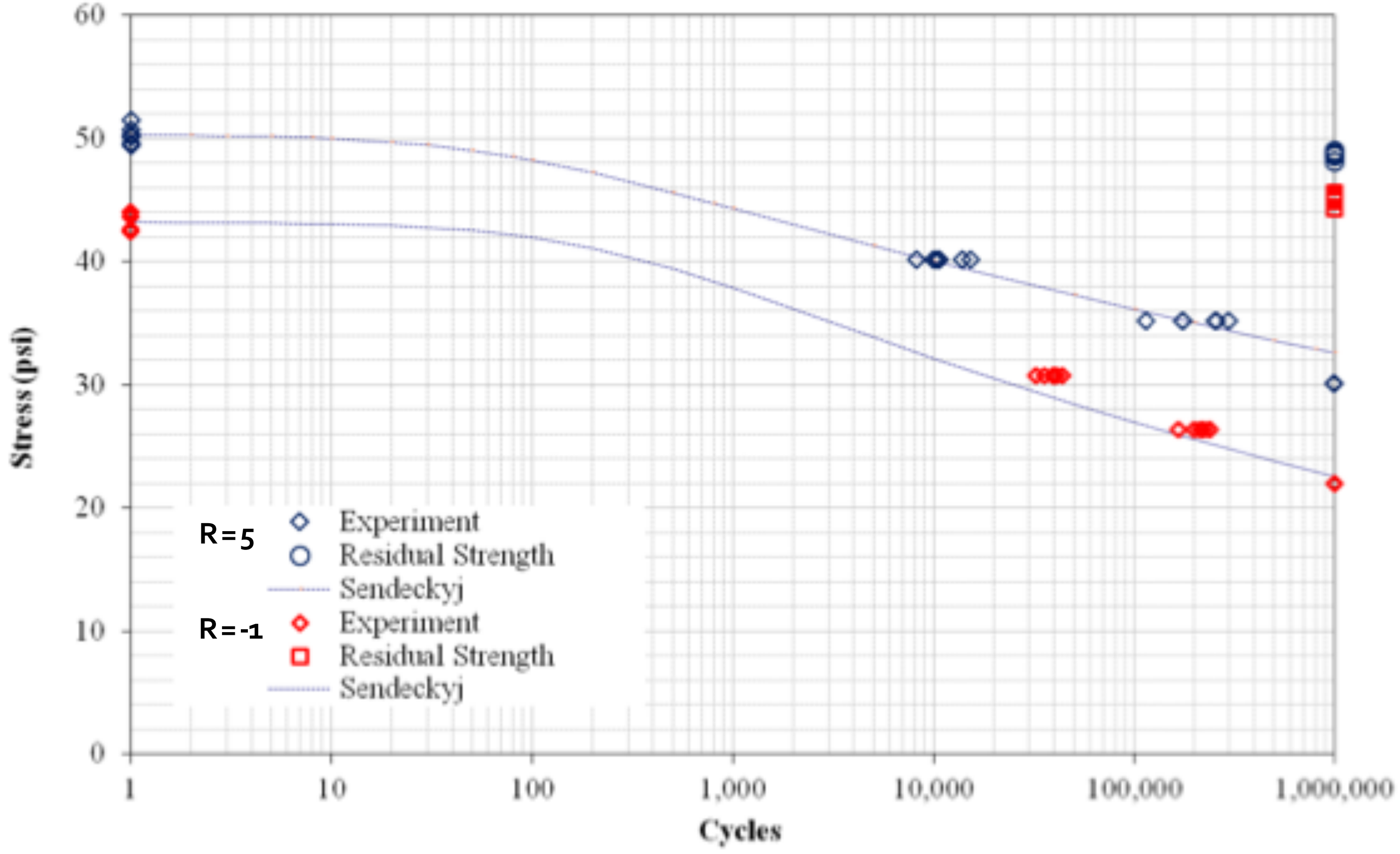


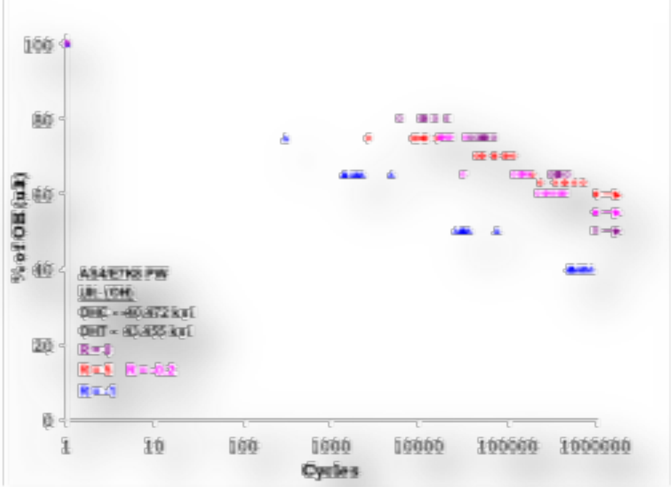
ST Method - Application

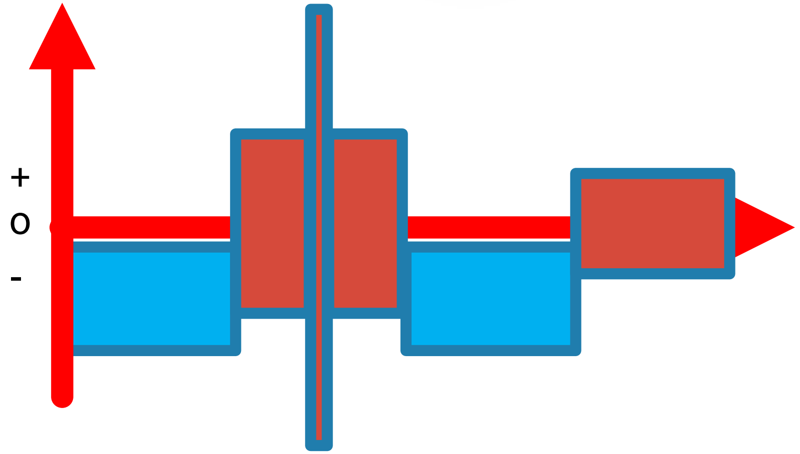
1. Fatigue testing and generate SN data
2. Fatigue data scatter analysis of SN data
   - Generate fitting parameters for Sendeckyj analysis
   - Fatigue data scatter is considered (reliability!)
3. Generate residual strength degradation models
4. Use the residual strength degradation for each block
   - Sequencing effects are considered
5. Predict residual strength degradation or fatigue life
   - Applied stress ≥ Residual strength → Fatigue failure



ST Method - Spectra with Multiple Stress Ratios

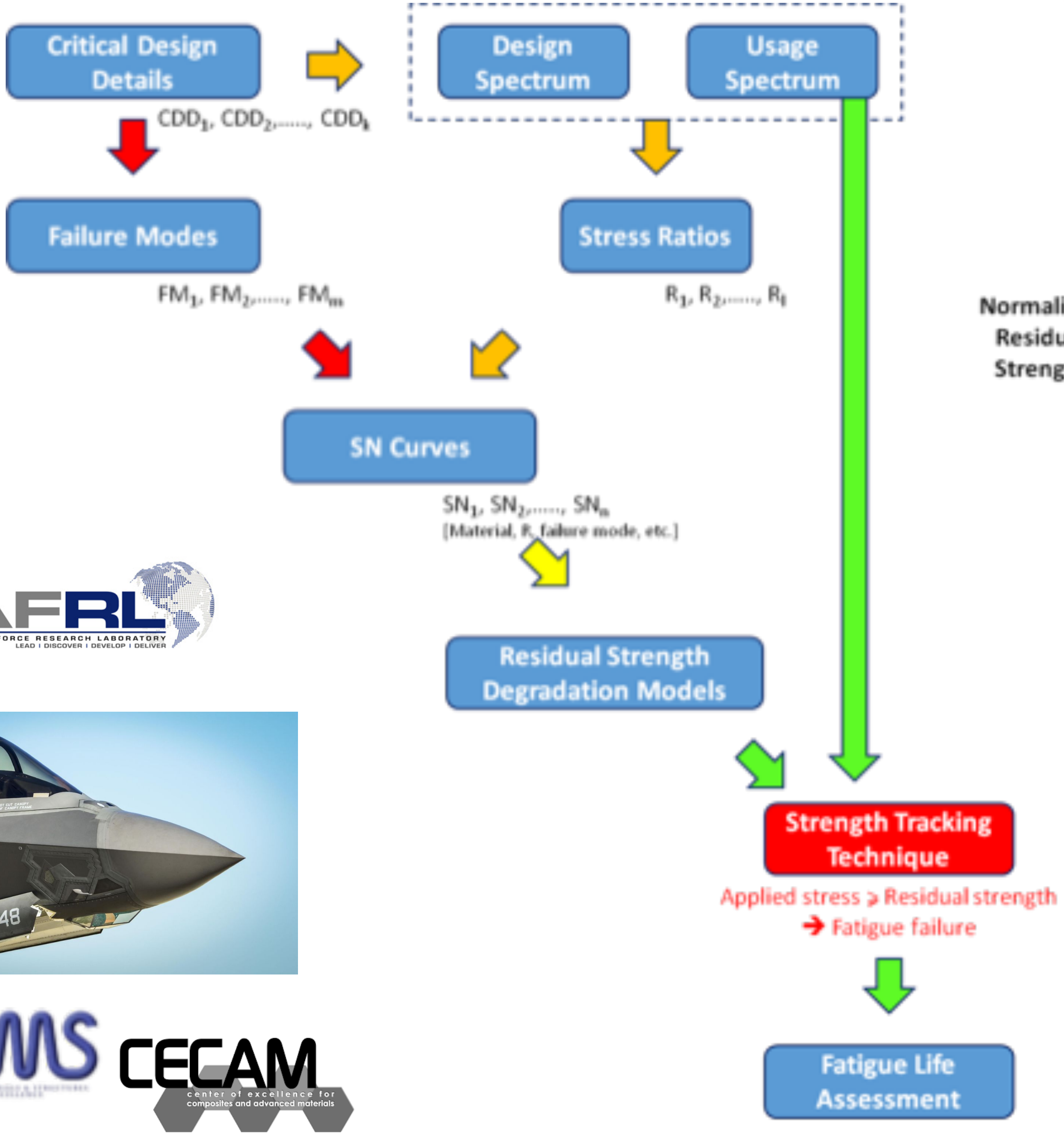


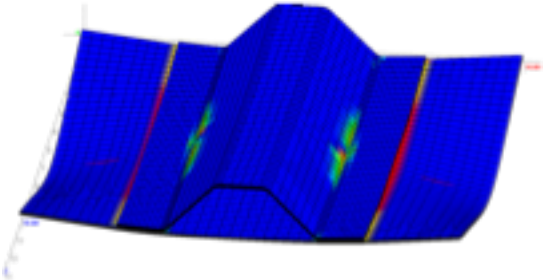




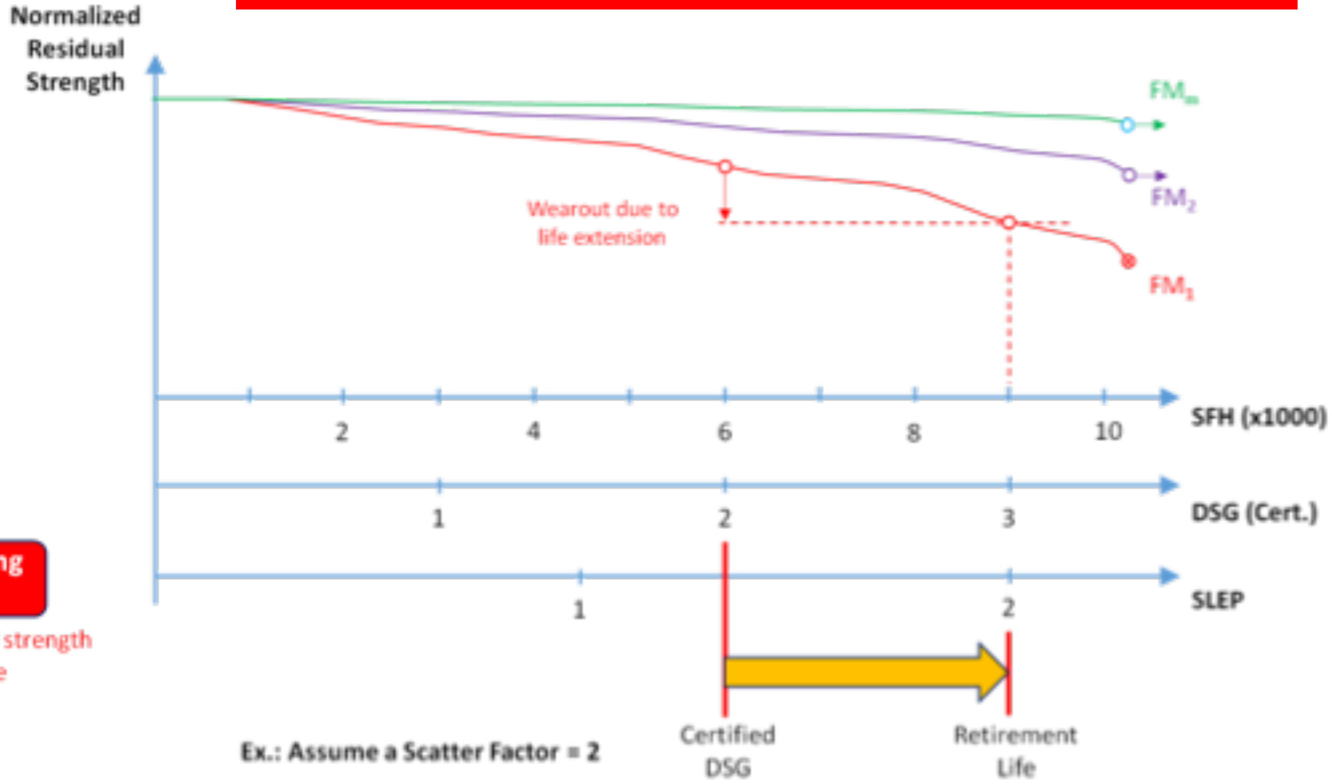
REF: Seneviratne, W. P., Tomblin, J. S., and Palliyaguru, U. **"Fatigue and Residual Strength Analysis of Out-of-Autoclave T650/5320 Plain Weave Fabric Composite Material,"** *CAMX 2014*.

ST Method for Structural Applications





Service Life Assessment & Service Life Extension



Spectrum Fatigue Test Results (25/50/25 PW)

		Load Block 1			Load Block 2			Load Block 3			Load Block 4			Load Block 5			
SPECIMEN #	R-Ratio	Max Stress [ksi]	Min Stress [ksi]	Cycles Survived	Max Stress [ksi]	Min Stress [ksi]	Cycles Survived	Max Stress [ksi]	Min Stress [ksi]	Cycles Survived	Max Stress [ksi]	Min Stress [ksi]	Cycles Survived	Max Stress [ksi]	Min Stress [ksi]	Cycles Survived	Total # of Cycles Survived
25-50-25-P1-OH-4	5	-6	-30	300000	-7	-35	50000	-8	-40	5000	-7	-35	50000	-6	-30	300000	705000
25-50-25-P1-OH-6	5	-6	-30	300000	-7	-35	50000	-8	-40	5000	-7	-35	50000	-6	-30	70210	475210
25-50-25-P1-OH-S	5	-6	-30	300000	-7	-35	50000	-8	-40	2423	-7	-35	-	-6	-30	-	352423
25-50-25-P2-OH-A	5	-6	-30	300000	-7	-35	50000	-8	-40	1936	-7	-35		-6	-30	-	351936
25-50-25-P2-OH-B	5	-6	-30	300000	-7	-35	50000	-8	-40	5000	-7	-35	50000	-6	-30	300000	705000
25-50-25-P2-OH-C	5	-6	-30	300000	-7	-35	50000	-8	-40	5000	-7	-35	7621	-6	-30	-	362621
25-50-25-P1-OH-7	-1	25	-25	200000	30	-30	10000	35	-35	43	30	-30	-	25	-25	-	210043
25-50-25-P1-OH-8	-1	25	-25	200000	30	-30	10000	35	-35	558	30	-30	-	25	-25	-	210558
25-50-25-P1-OH-9	-1	25	-25	200000	30	-30	10000	35	-35	125	30	-30	-	25	-25	-	210125
25-50-25-P1-OH-T	-1	25	-25	174580	30	-30	-	35	-35	-	30	-30	-	25	-25	-	174580
25-50-25-P1-OH-U	-1	25	-25	200000	30	-30	190	35	-35	-	30	-30	-	25	-25	-	200190
25-50-25-P1-OH-V	-1	25	-25	200000	30	-30	1477	35	-35	-	30	-30	-	25	-25	-	201477
25-50-25-P2-OH-7	-1	25	-25	200000	30	-30	5000	35	-35	83	30	-30	-	25	-25	-	205083
25-50-25-P2-OH-8	-1	25	-25	200000	30	-30	5000	35	-35	70	30	-30	-	25	-25	-	205070
25-50-25-P2-OH-9	-1	25	-25	200000	30	-30	5000	35	-35	533	30	-30	-	25	-25	-	205533
25-50-25-P2-OH-D	-1 & 5	-6	-30	200000	25	-25	200000	-7	-35	20000	30	-30	-			-	420000
25-50-25-P2-OH-E	-1 & 5	-6	-30	200000	25	-25	200000	-7	-35	5122	30	-30	-			-	405122
25-50-25-P2-OH-F	-1 & 5	-6	-30	200000	25	-25	200000	-7	-35	20000	30	-30	1213			-	421213

Validation of ST Method – 25/50/25 PW Preliminary Results

Fatigue Analysis

	25/50/25											
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.254	0.045	0.015	5	30	-6.000	-30.000	300000	0	300000	50.143
2	300000	50.254	0.045	0.015	5	35	-7.000	-35.000	50000	9760	59760	49.470
3	350000	50.254	0.045	0.015	5	40	-8.000	-40.000	5000	3075	8075	46.992
4	355000	50.254	0.045	0.015	5	35	-7.000	-35.000	45517	156963	202480	35.007
									400517			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	44.923	0.077	0.005	-1	25	25.000	-25.000	200000	0	200000	42.930
2	200000	44.923	0.077	0.005	-1	30	30.000	-30.000	10000	18623	28623	41.101
3	210000	44.923	0.077	0.005	-1	35	35.000	-35.000	1000	3847	4847	38.537
4	211000	44.923	0.077	0.005	-1	30	30.000	-30.000	4609	36065	40674	33.878
									215609			
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.254	0.045	0.015	5	30	-6.000	-30.000	200000	0	200000	50.180
2	200000	44.923	0.077	0.005	-1	25	25.000	-25.000	200000	-1445345	-1245345	49.752
3	400000	50.254	0.045	0.015	5	35	-7.000	-35.000	20000	40512	60512	49.458
4	420000	44.923	0.077	0.005	-1	30	30.000	-30.000	12373	-104239	-91866	49.123
									432373			

Fatigue Test Results

R = 5

705000	
475210	475210
352423	352423
351936	351936
705000	
362621	362621
492032	**385548**

R = -1

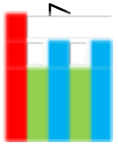
1	210043
1	210558
1	210125
2	174580
2	200190
2	201477
2	205083
2	205070
2	205533
	202518

R = 5 & -1

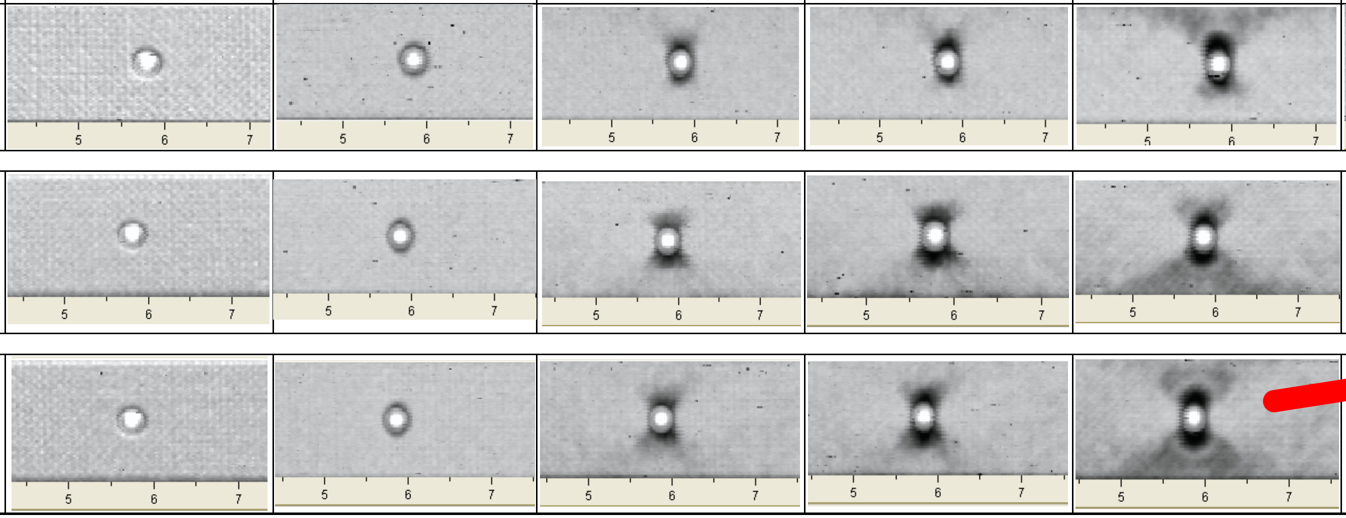
420000
405122
421213
415445

Validation of ST Method – 25/50/25 PW Load Sequencing

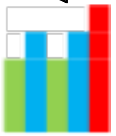
70-40-55-40-55 (High-Low)



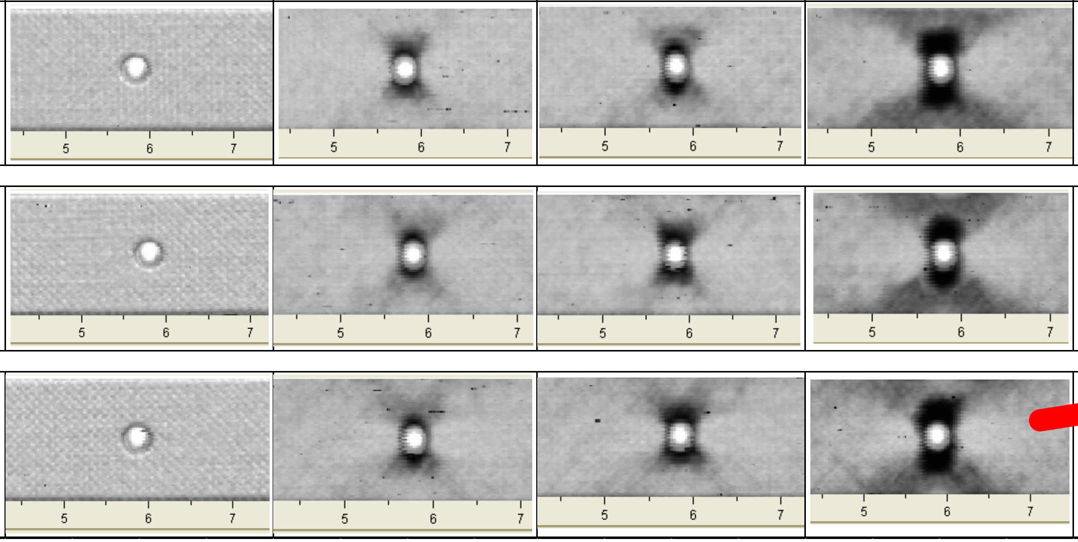
Fatigue Profile 5	NAME	n=0 Reference	70% - n=1,040 Load Block 1	40% - n=401,050 Load Block 2	55% - n=415,610 Load Block 3	40% - n=815,620 Load Block 4	55% - n=830,180 Load Block 5
	PW-OH-27						
	PW-OH-1						Failed at 823,523 cycles
	PW-OH-2						Failed at 827,830 cycles

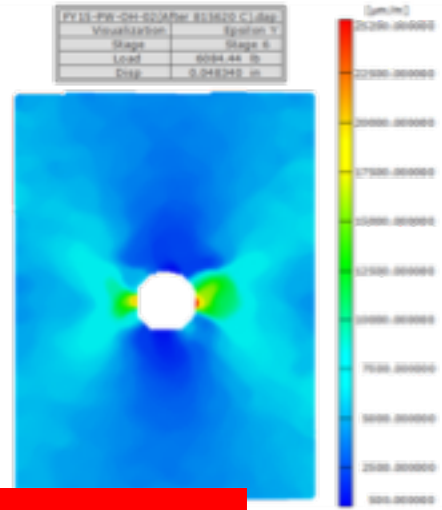


40-55-40-55-70 (Low-High)

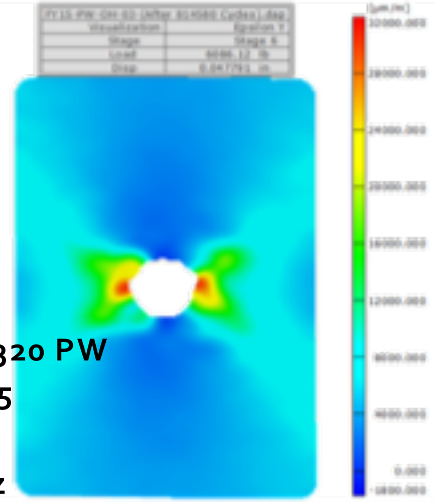


Fatigue Profile 6	NAME	n=0 Reference	40% - n=400,010 Load Block 1	55% - n=414,570 Load Block 2	40% - n=814,580 Load Block 3	55% - n=429,140 Load Block 4	70% - n=430180 Load Block 5
	PW-OH-3					Failed at 815,550 cycles	
	PW-OH-4					Failed at 822,849 cycles	
	PW-OH-6					Failed at 816,002 cycles	





ST Predictions
n = 830,180



T650/5320 PW
25/50/25
R = -1
F = 5 Hz

Validation of ST Method – 40/20/40 PW Preliminary Results

Fatigue Analysis

	40/20/40	[0/90/0/90/45/-45/90/0/90/0]s										
Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.847	0.035	0.209	5	30	-6.000	-30.000	500000	0	500000	50.798
2	500000	50.847	0.035	0.209	5	35	-7.000	-35.000	50000	5961	55961	50.327
3	550000	50.847	0.035	0.209	5	40	-8.000	-40.000	3000	1207	4207	47.066
4	553000	50.847	0.035	0.209	5	35	-7.000	-35.000	23766	195134	218900	35.217
									576766			

Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	51.298	0.080	0.006	-1	25	25.000	-25.000	500000	0	500000	49.503
2	500000	51.298	0.080	0.006	-1	30	30.000	-30.000	50000	50465	100465	46.374
3	550000	51.298	0.080	0.006	-1	35	35.000	-35.000	3000	14452	17452	43.663
4	553000	51.298	0.080	0.006	-1	30	30.000	-30.000	18240	121320	139560	30.013
									571240			

Block	Σ n	σ_e	S	C	R	σ_a	σ_{max}	σ_{min}	n_i	n_{eqv}	n_{tot}	$\sigma_r(n,R,\sigma)$
1	0	50.847	0.035	0.209	5	30	-6.000	-30.000	500000	0	500000	50.798
2	500000	51.298	0.080	0.006	-1	25	25.000	-25.000	500000	160578	660578	48.721
3	1000000	50.847	0.035	0.209	5	35	-7.000	-35.000	50000	154754	204754	46.224
4	1050000	47.509	0.070	0.038	-1	30	30.000	-30.000	12334	5893	18227	30.071
									1062334			

Fatigue Test Results

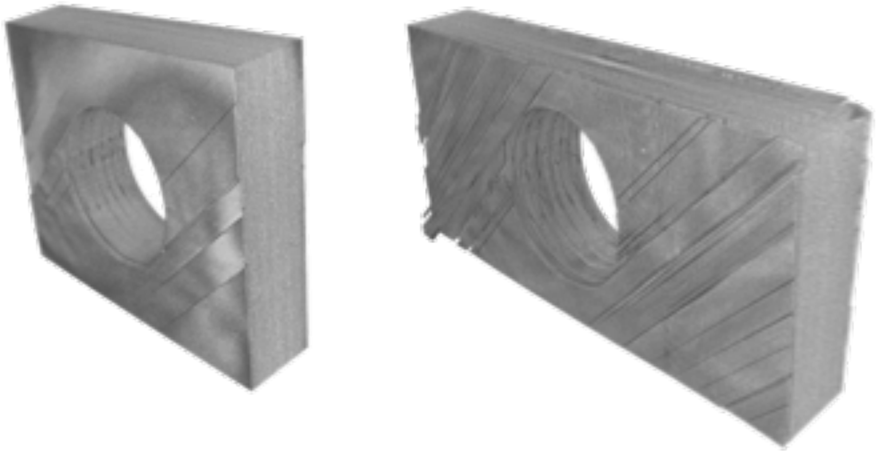
3 Specimens of R = 5 survived 1,103,00 cycles

R = -1
550,165
539,141
523,164
521,419
533,781
522,465
531,689

R = 5 & -1	R = -1 & 5
1,015,810	1,000,190
1,046,541	1,006,941
1,050,001	1,035,966
1,037,451	1,014,366

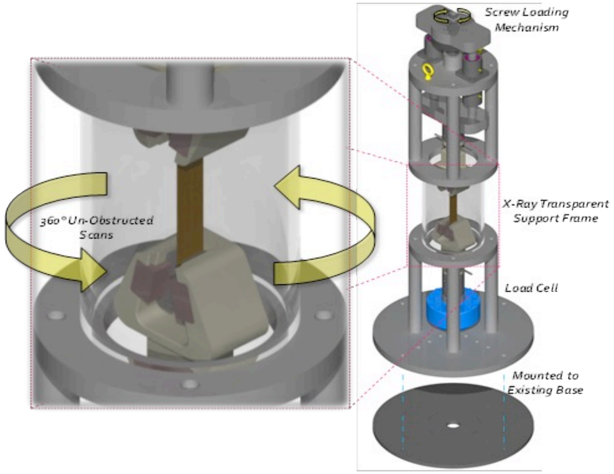
High-Fidelity Inspections for Damage Characterization

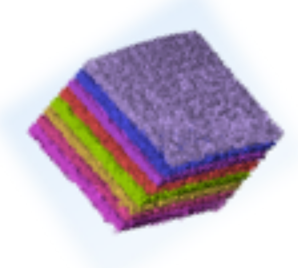
X-Ray Computed Tomography (XCT)



High-Fidelity Inspections: NSI X7000 X-Ray CT System

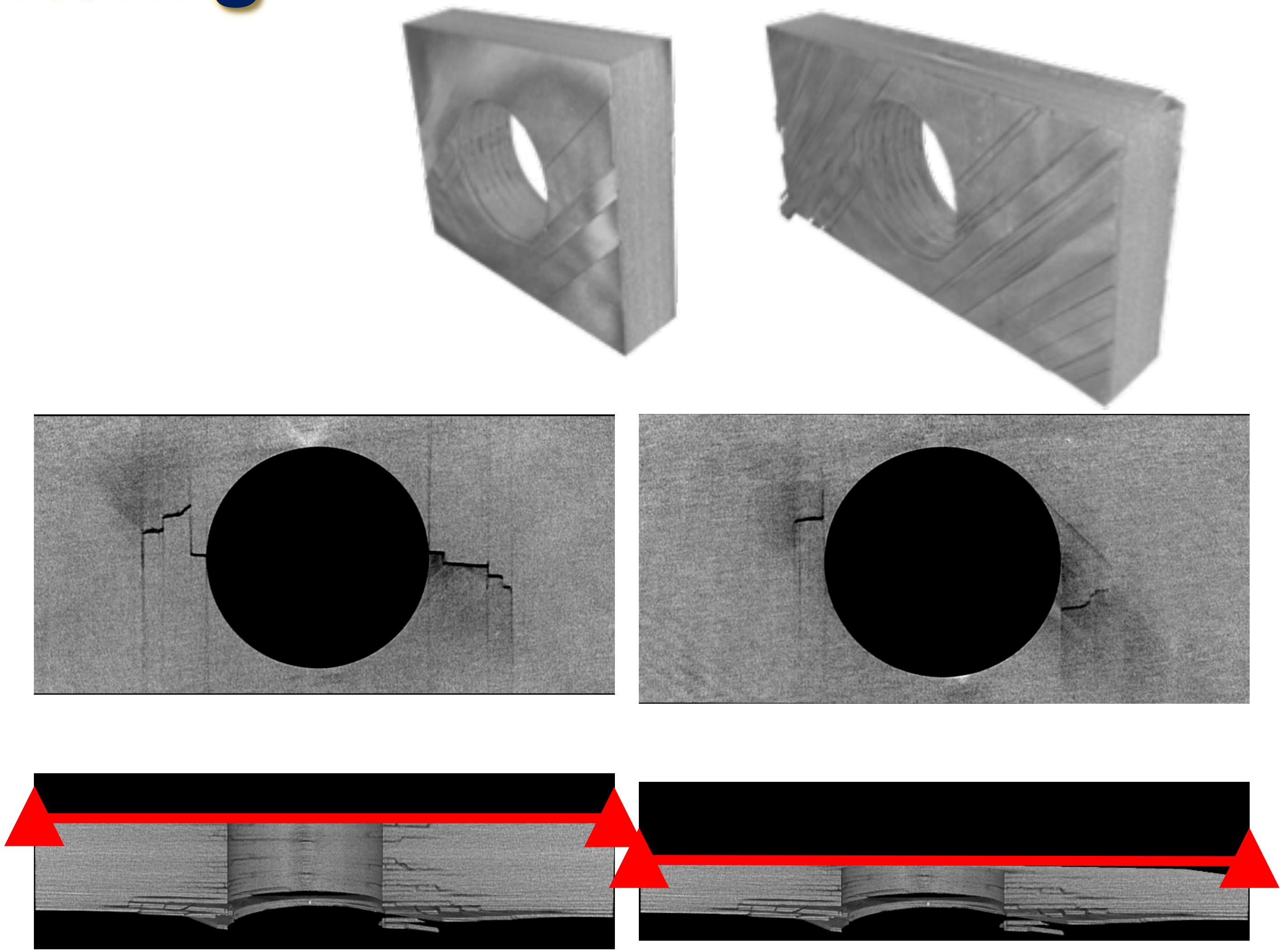
- ***Dual* X-ray Tubes**
  - 225kV Micro-focus (6 μm) for low attenuating/low density materials, e.g. Carbon Fiber Composites.
  - 450 kV Mini-focus for high attenuating/high density materials, e.g. Metals
- ***Dual* Detectors**
  - Perking Elmer flat panel detector 16″× 16″
  - Linear Diode Array (LDA) allows high precision data acquisition
- **Software**
  - NSI proprietary software for reconstruction of 3D volume
  - Materialise Mimics and 3Matic is used for data segmentation and data export into formats conducive for analysis
- **Portable Load Fixture**





X-Ray CT: Damage Monitoring

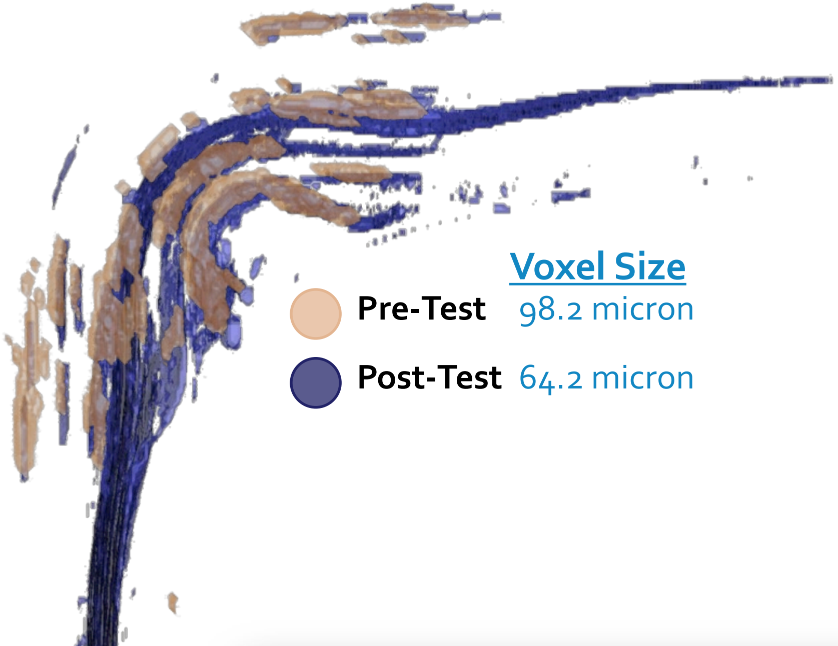
- High-fidelity ply-by-ply damage information
- Initiation site(s) detection and propagation details
- Interaction of different failure modes
- Multi-site damage interactions

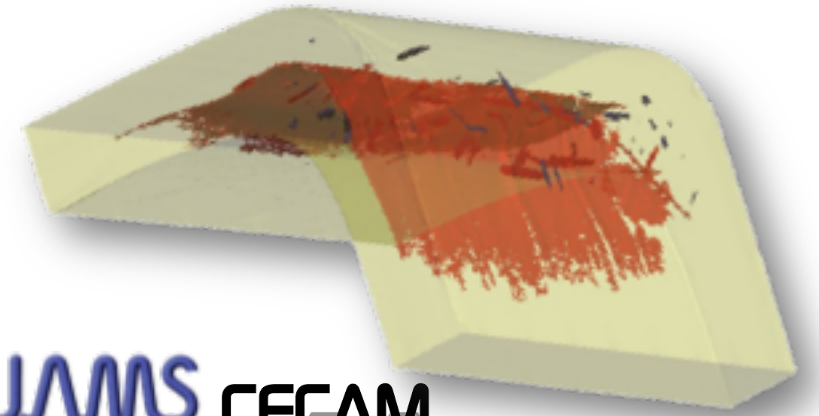


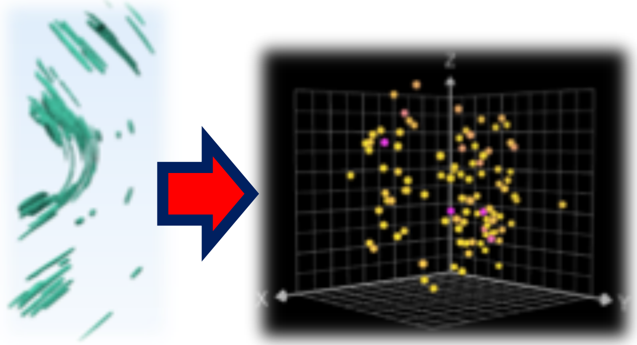
Fatigue damaged open-hole test specimen

Feature Segmentation – Effects of Defects

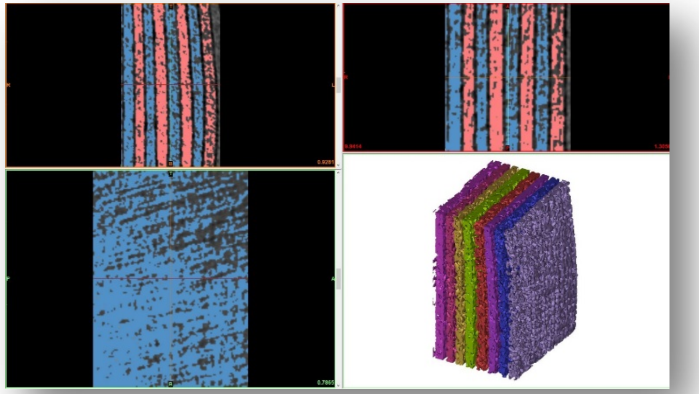
- Segment and isolate the features of interest in Mimics
- These features can be meshed and exported as STL files for further analysis
- This information can be used as input parameters for damage modeling





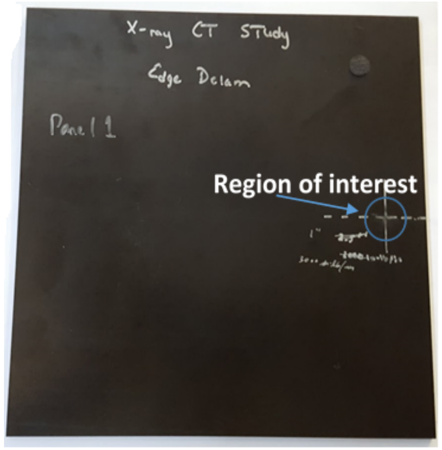


Spatial distribution of defects

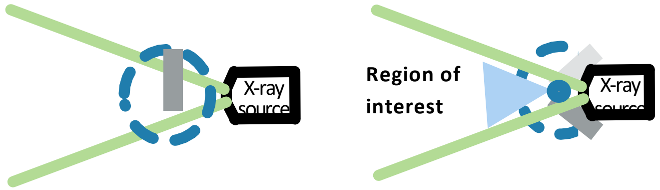


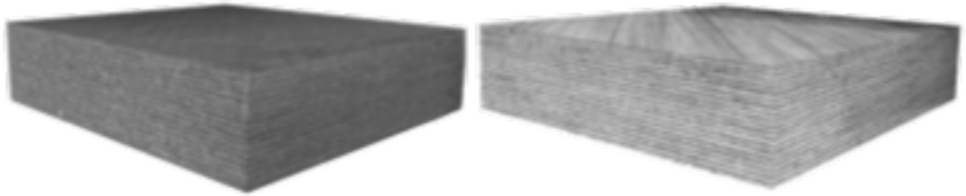
Technique Development

- Partial Rotation vs Full Rotation
  - Usually CT captures images from 360° around the object.
  - Using partial rotation scans it is possible to obtain higher resolution images of a smaller area.
  - This is a useful option to have when the object dimensions are larger than the area of interest.
  - Number of projections can be increased.

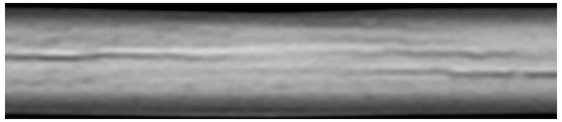


Area of interest can be moved closer to the source improving resolution.

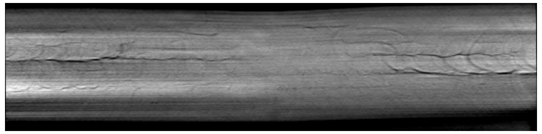




Full rotation scans

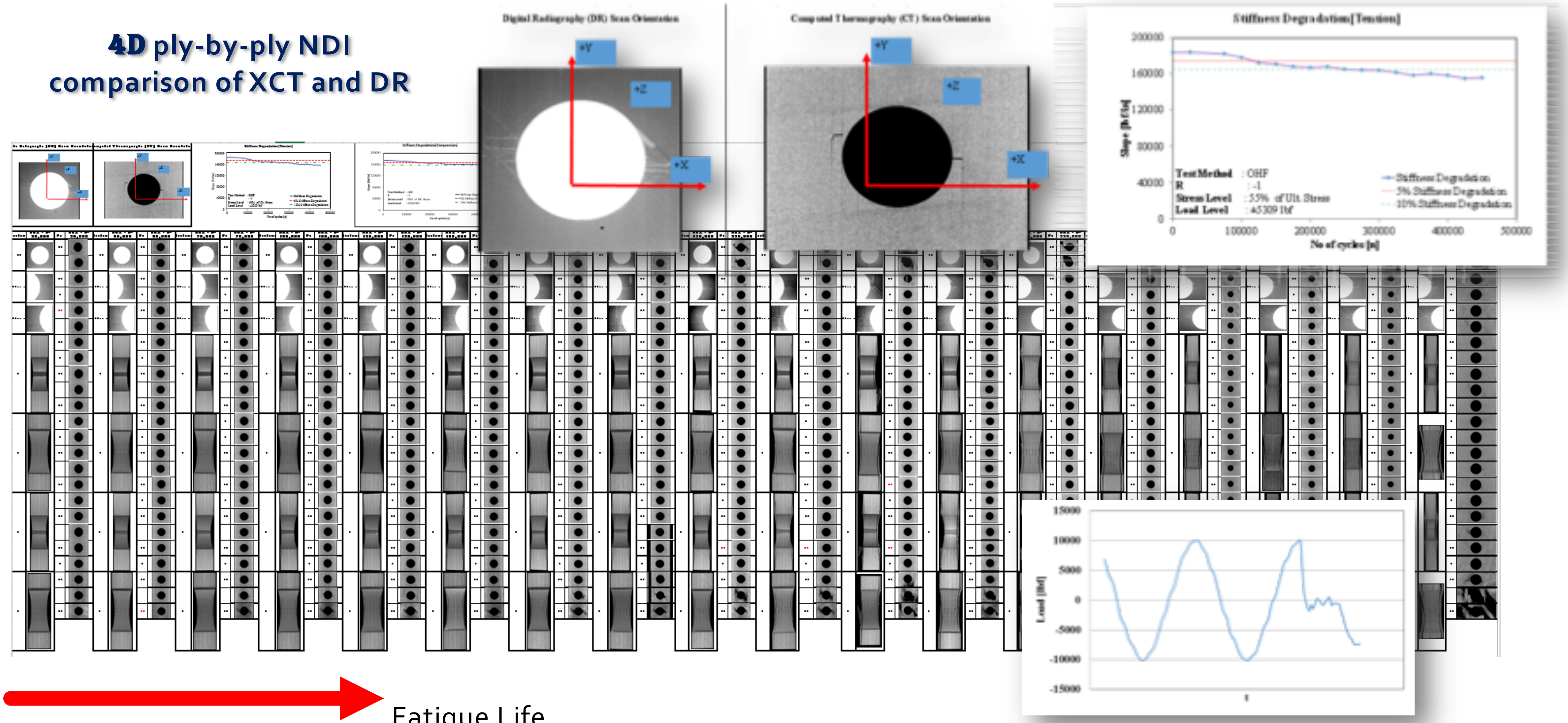


Partial rotation scans



High-Fidelity NDI for Damage Characterization (Database)

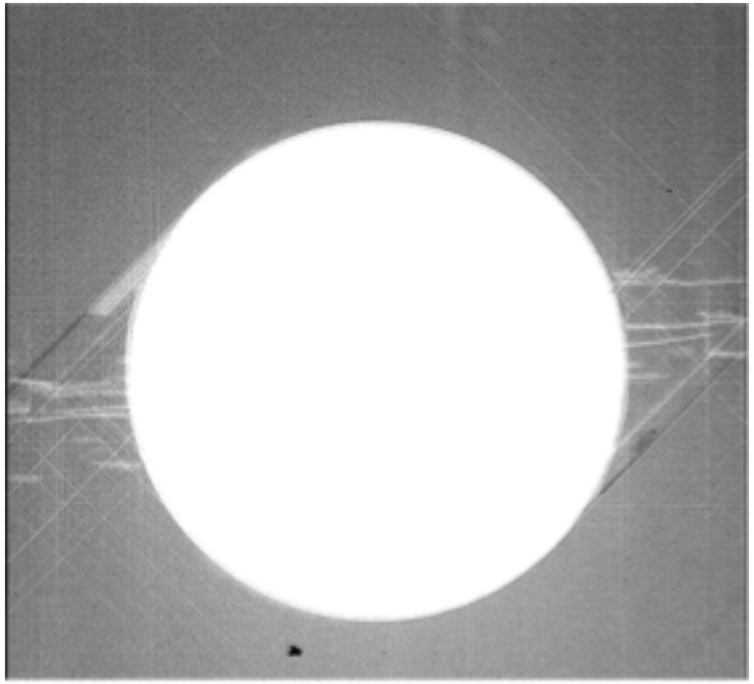
4D ply-by-ply NDI
comparison of XCT and DR



Fatigue Life

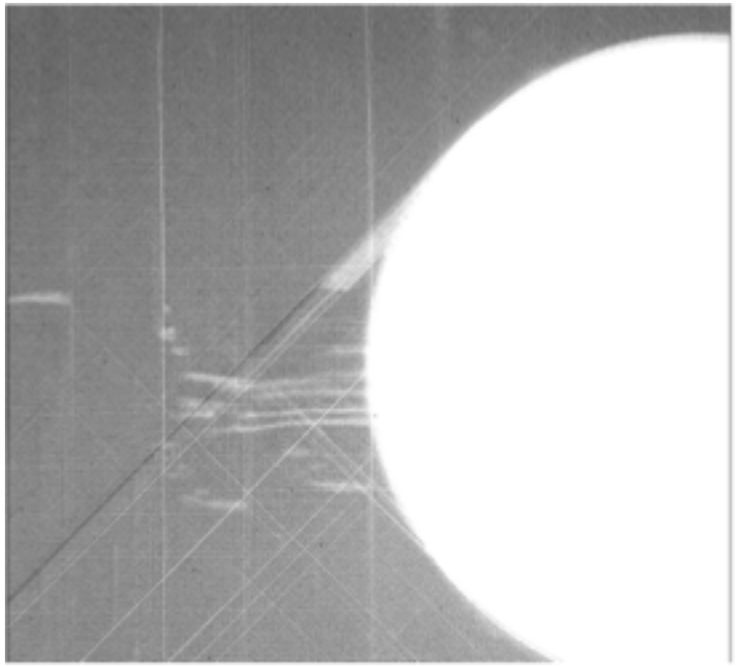
DR vs. CT for Characterizing Fatigue Damage

DR

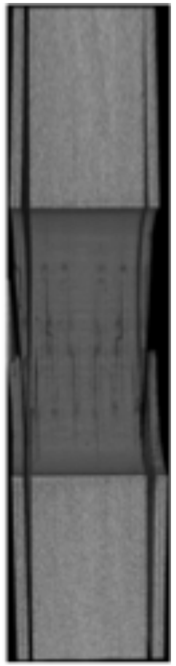


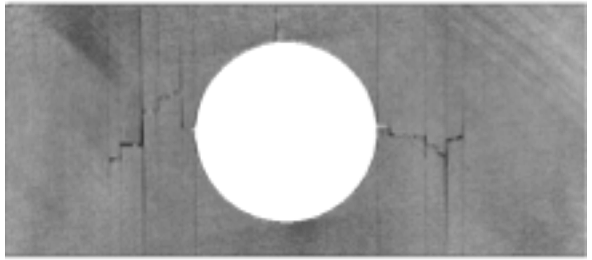
CT

DR



CT

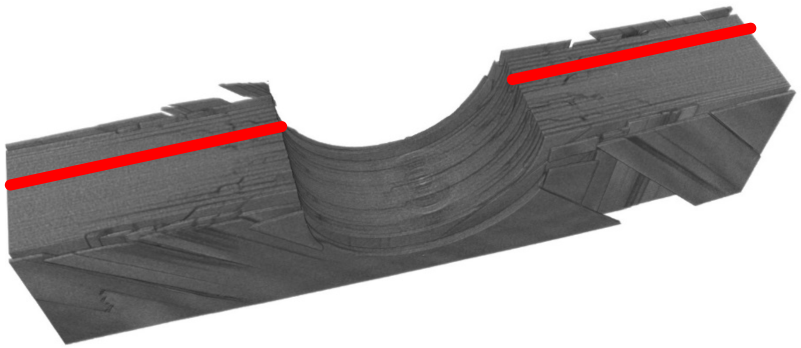


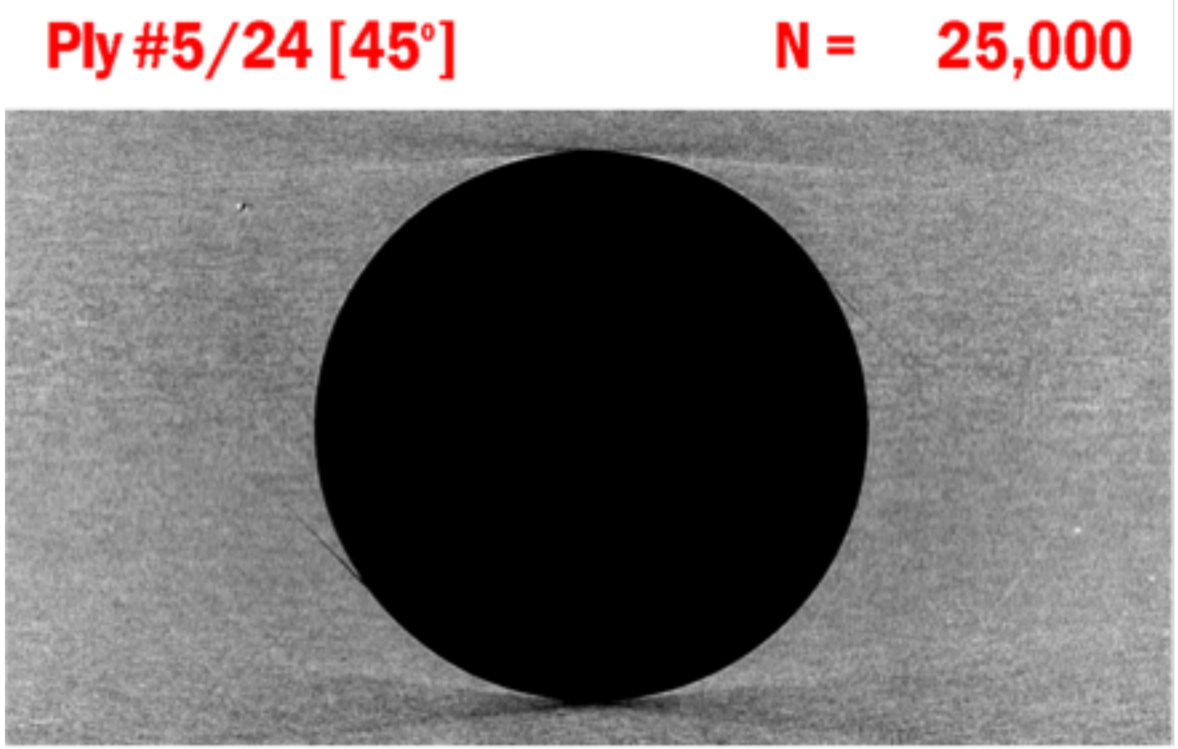


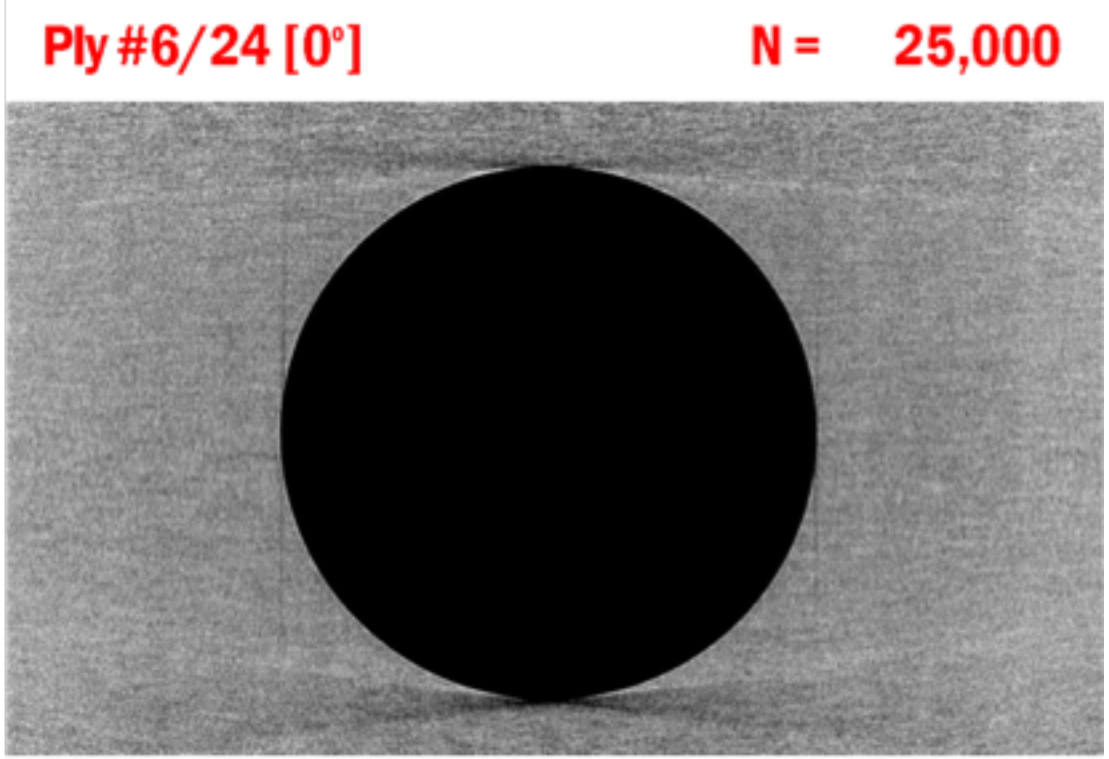
CT

4D XCT - Fatigue Damage Progression (Ply-by-Ply)

- OH-UNI-10 $[45/0/-45/90]_{3s}$
  - Stress level – 55% (27.3 ksi)
  - R = -1





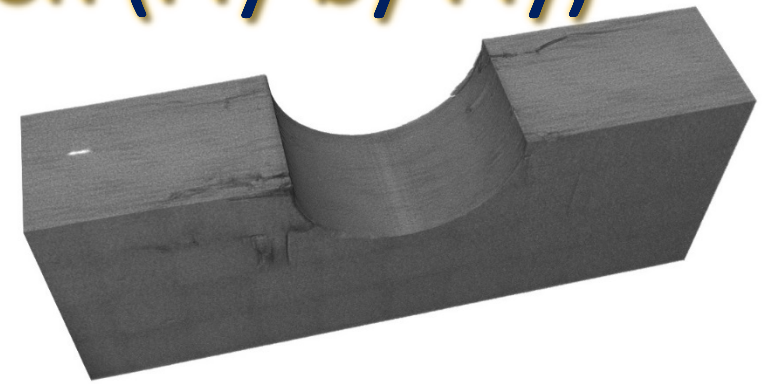


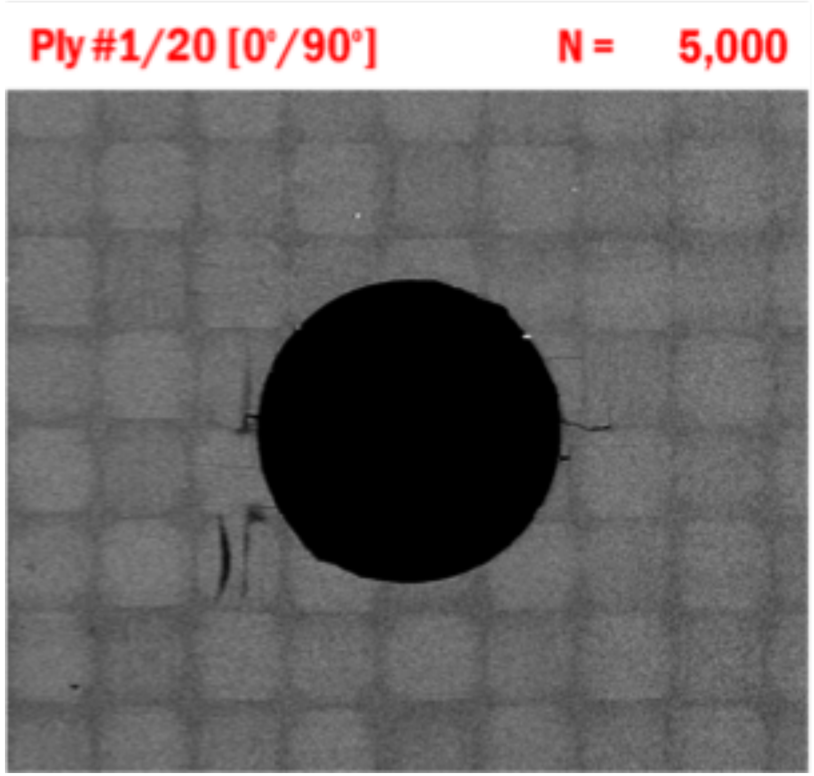
3D XCT - Open-Hole (Plain Weave fabric)

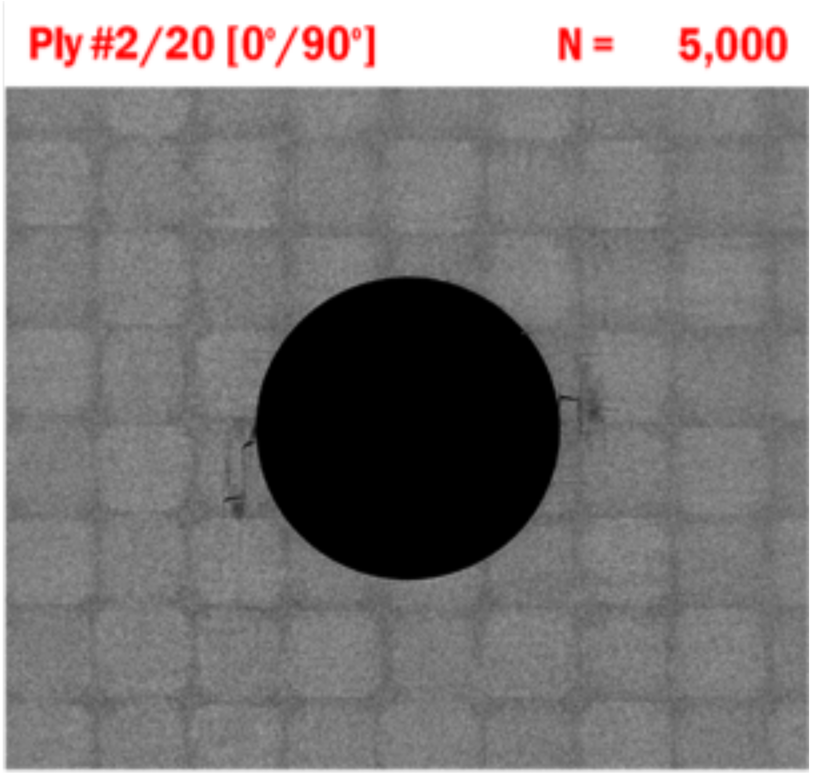
T650/5320-1 PW
PW-OHC-8 (40/20/40)
Quasi-Isotropic
Constant Amplitude (R = -1)
Stress Level = 35 ksi
n = 22,250

4D XCT - Fatigue Damage Progression (Ply-by-Ply)

- OH-PW-8 [0/90/0/90/45/-45/90/0/90/0]s
  - Stress = 35 ksi
  - R = -1
  - n= 25630







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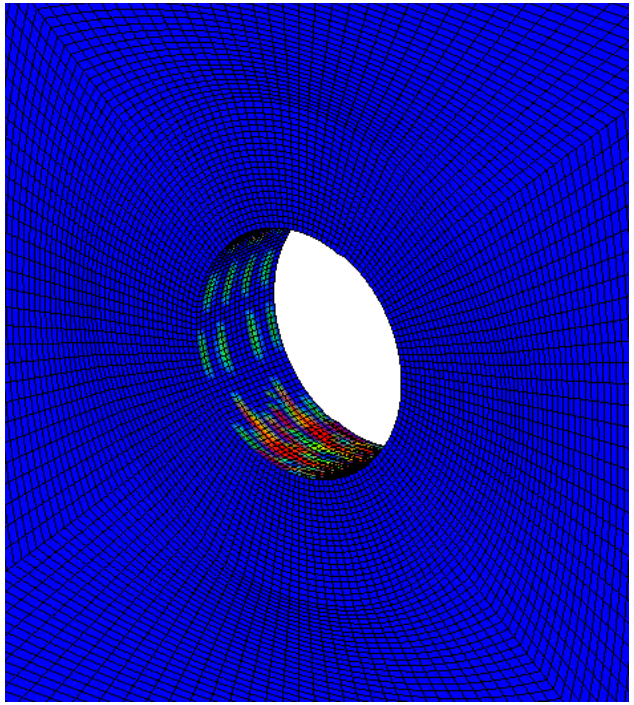
High-Fidelity Finite Element Analysis

Regularized Extended Finite Element Analysis (Rx-FEM)



High-Fidelity Analysis

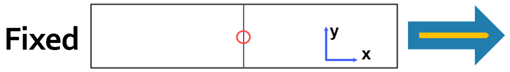
Mesh-independent regularized extended finite element modeling (Rx-FEM)

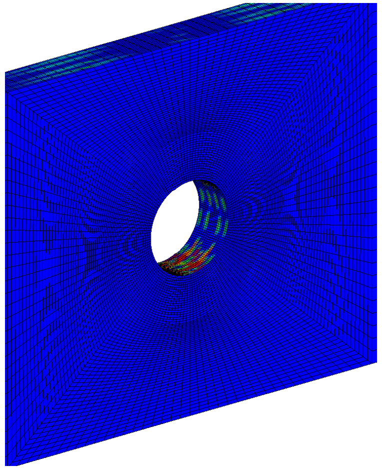
Delamination and open matrix cracks

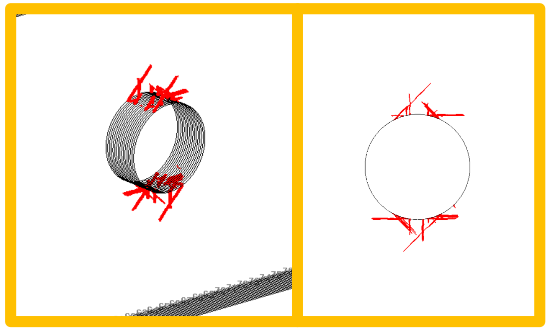
@ predicted <u>failure strength</u> of 375MPa

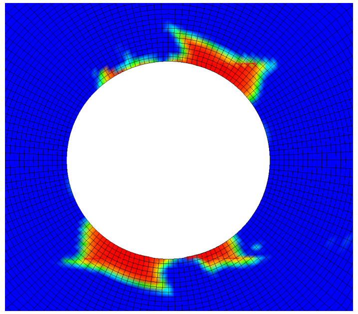
[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]

1 2 3 4



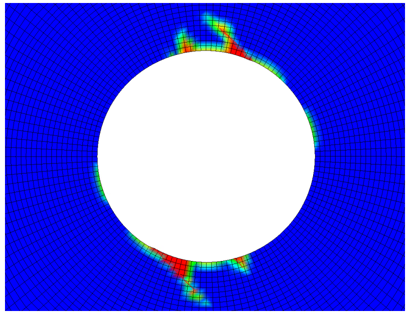






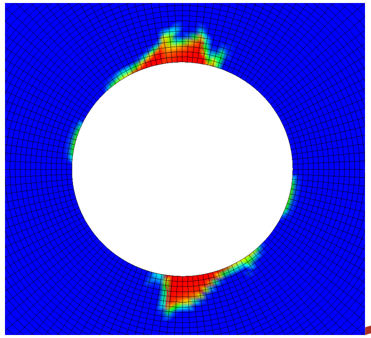
1

0° Ply



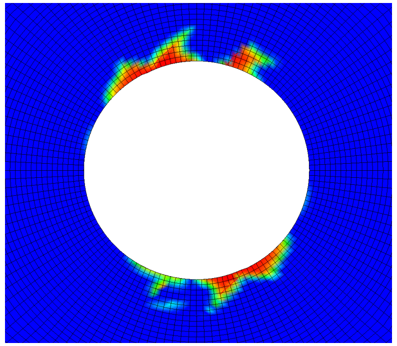
2

-45° ply



3

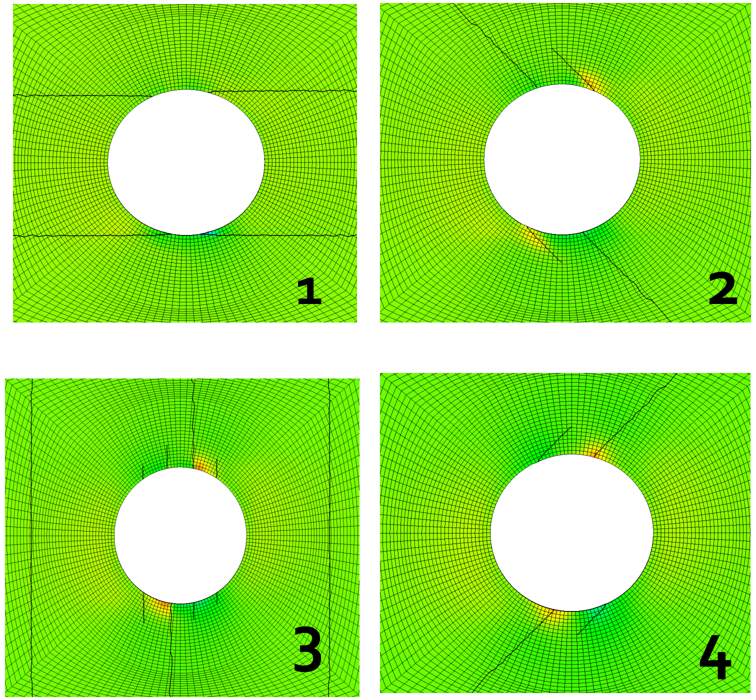
90° ply



4

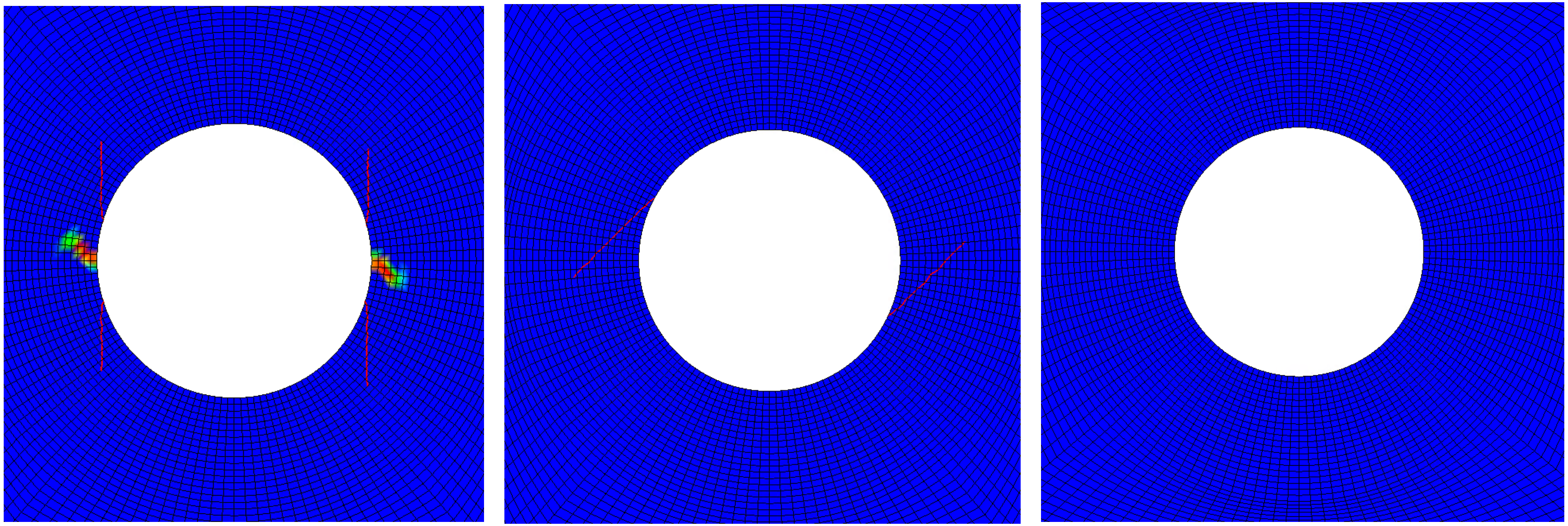
45° ply

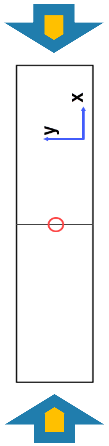
Potential "crack path" if crack continued



Rx-FEM - Matrix and Fiber Cracks in UNI OHC

0° ply -45° ply 90° ply



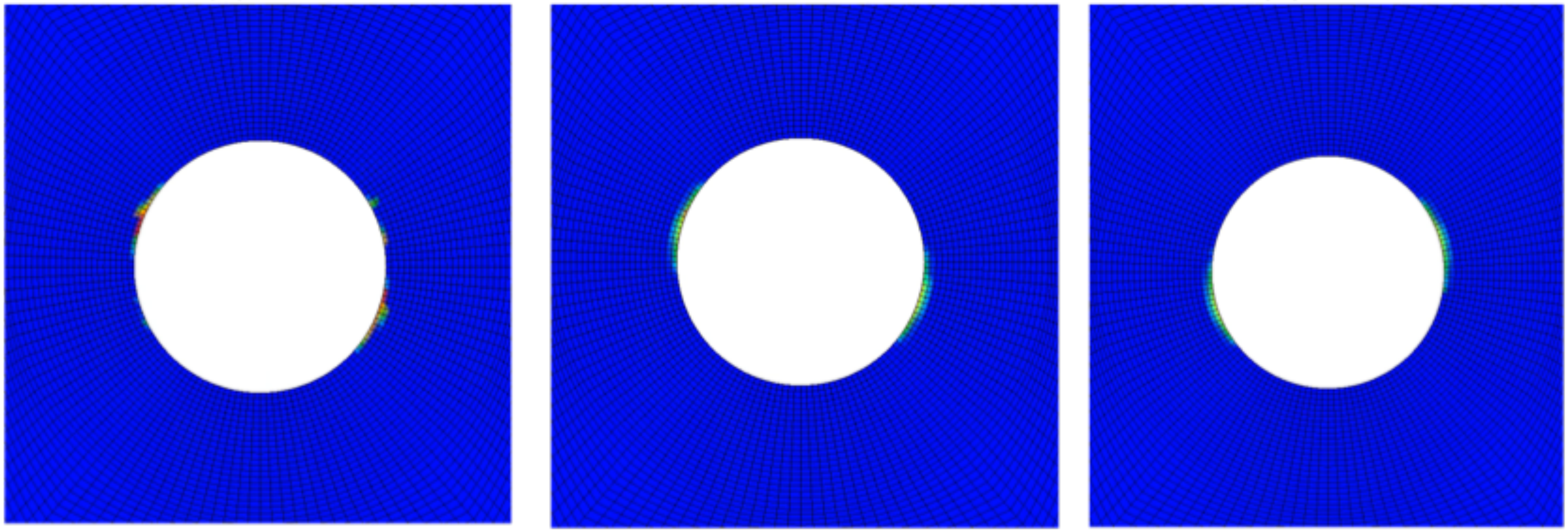


Fiber break near hole on 0°

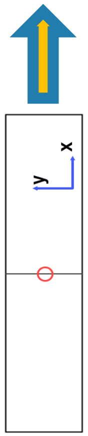
[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]

Rx-FEM - Delamination Propagation in UNI OHT

0° ply | -45° ply | 90° ply



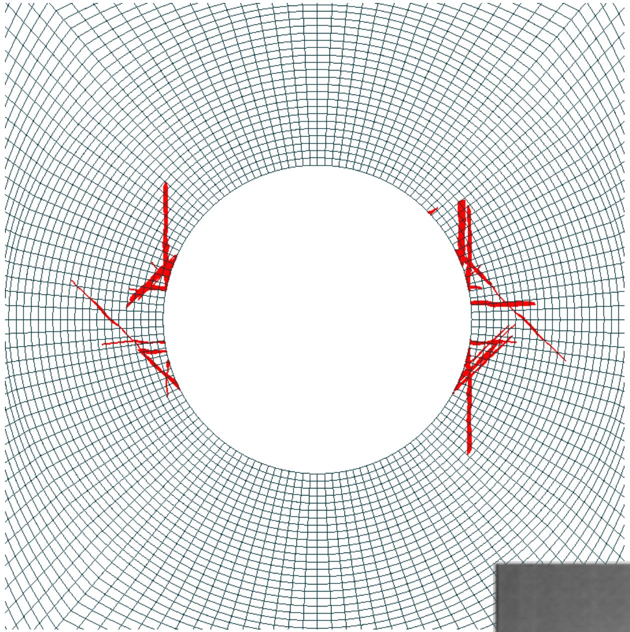
Delamination in 0/-45 interface | Delamination in -45/90 interface | Delamination in 90/45 interface

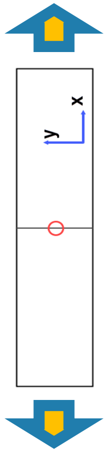


Fixed

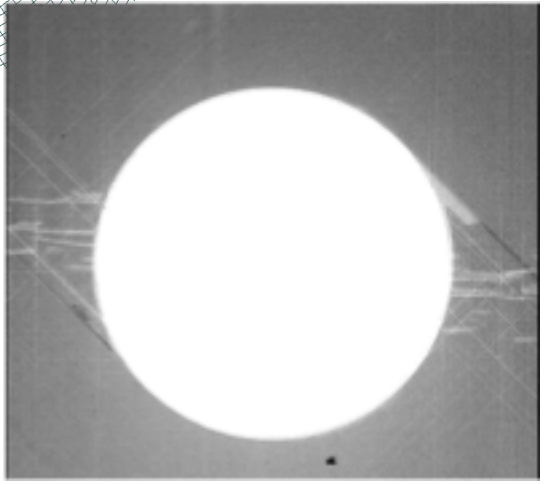
[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]

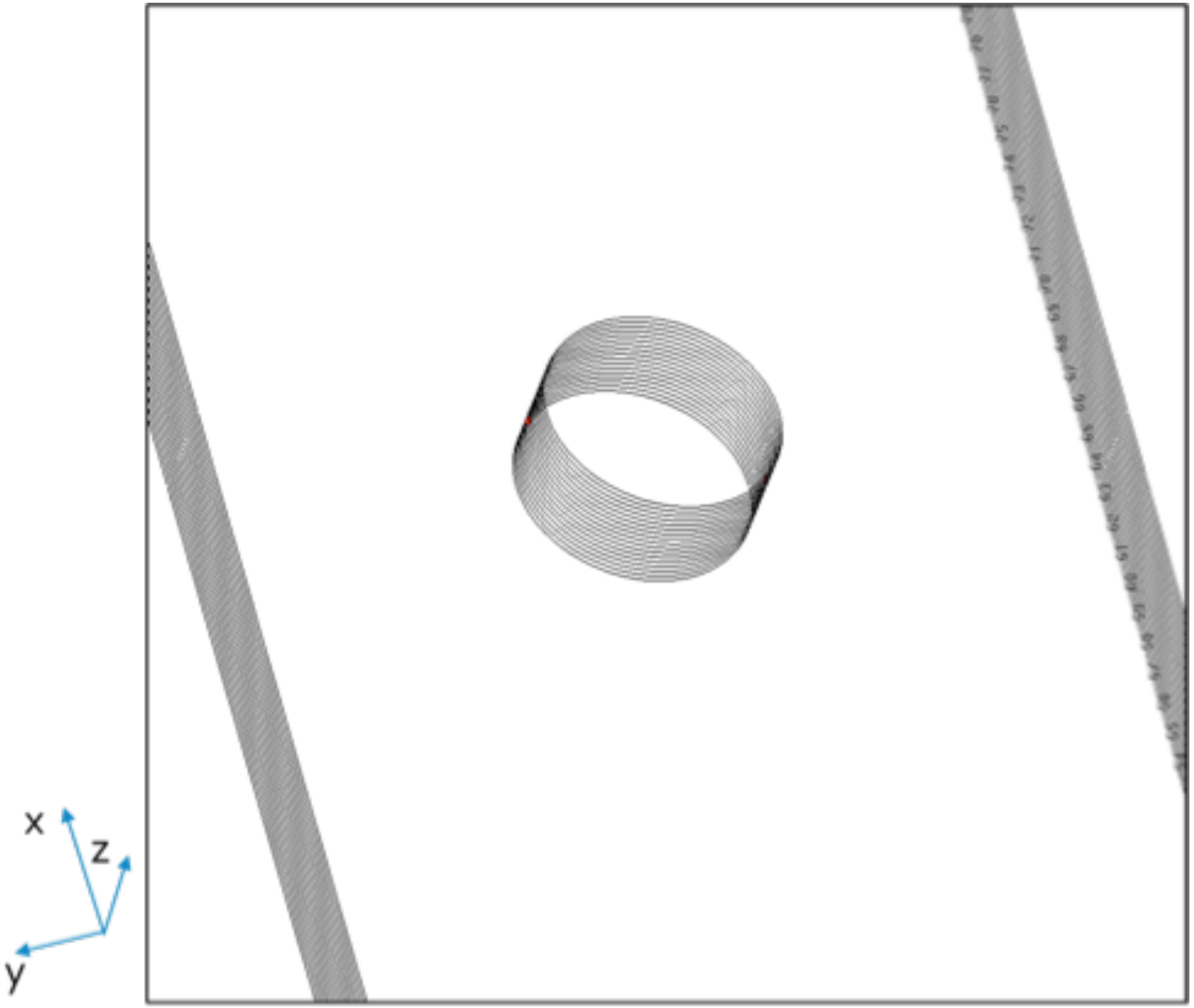
Rx-FEM - Matrix Crack Growth in UNI OHT



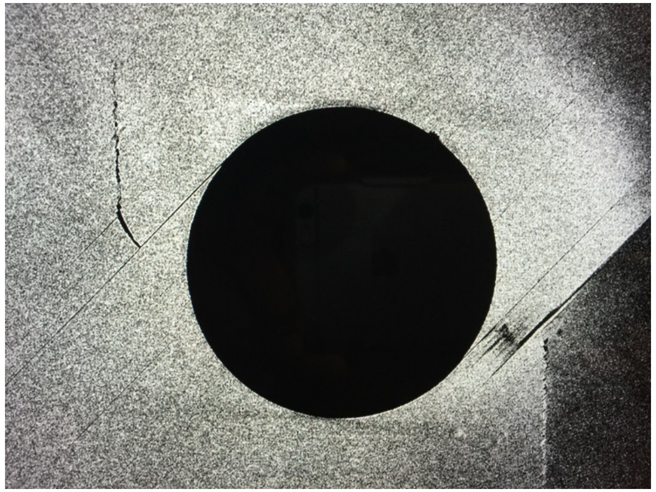


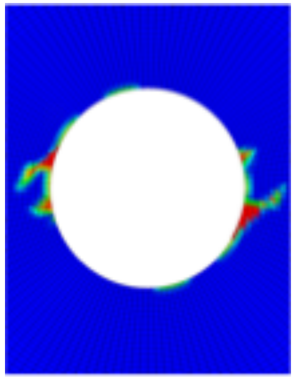
[45/90/-45/0]2S





3D XCT UNI OH

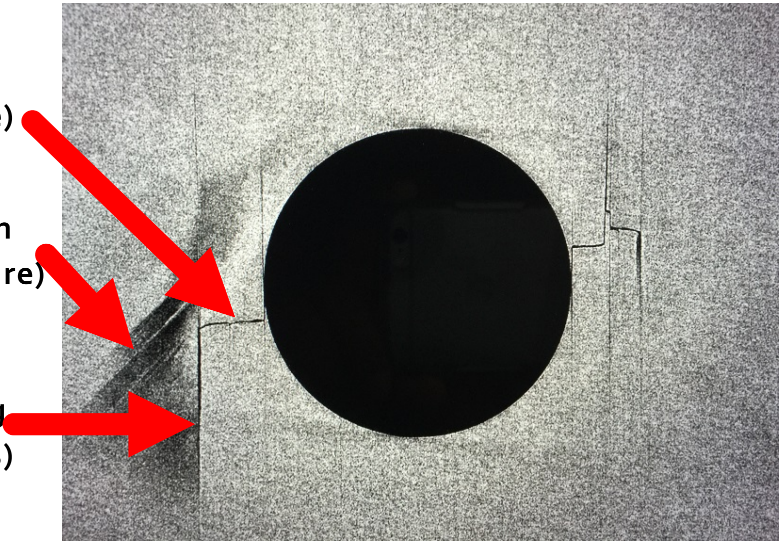




Fiber Break
(Fiber Failure)

Delamination
(Interface Failure)

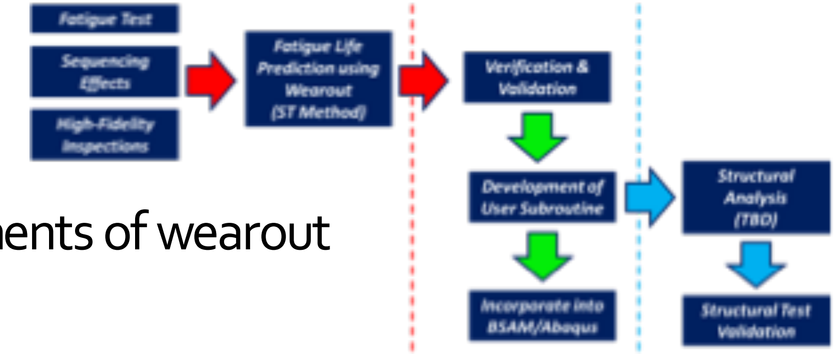
Fiber Splitting
(Matrix Cracks)



T650/5320-1 UNI (UNI-OHC-15)
Quasi-Isotropic; R = -1; 55% Stress level; n = 200,000

Summary - Strength Tracking (ST) Method

- Fatigue damage growth of composites under constant or variable amplitude (block/random) fatigue loading can be assessed
  - Can handle multiple R ratios
  - Sequencing effects will be incorporated
- Any validated residual strength degradation (wearout) model can be used
  - Sendeckyj wearout model is used for examples due to its robustness (ex., fitting curve for SN data provides an assessment of fitting parameters)
    - Incorporate reliability (analysis of fatigue data scatter)
    - Residual strength degradation for arbitrary stress levels
    - Simple Excel worksheet can be setup for life assessment
  - Provide opportunity to improve the technique for future developments of wearout models, both semi-empirical and analytical models



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Summary – Damage Characterization (XCT)

- XCT system has significantly enhanced the research quality
  - Provided insight to interrogate internal defects/features of various material systems
  - Damage growth mechanics of advanced material systems under cyclic loading
  - Post-failure and accident investigation without sectioning
- Technique development is underway to enhance the quality of inspections
- Mimics software is used successfully for segmentation of various features from XCT reconstructions for analyses

NIAR Wichita State University
National Institute for Aviation Research

NSI North Star Imaging
An ITW Company

Materialise Mimics

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Looking Forward

- **Benefit to Aviation**
  - High-fidelity database of fatigue damage growth characteristics of composites under variable amplitude fatigue loading
  - Development of engineering tools for determining the residual strength degradation and fatigue life under variable amplitude fatigue cycling
- **Future needs**
  - Variable amplitude fatigue data for fatigue analysis and validation of wearout models for analytical life predictions
  - Analytical models for predicting residual strength degradation (wearout)